Wolfgang Lutz,
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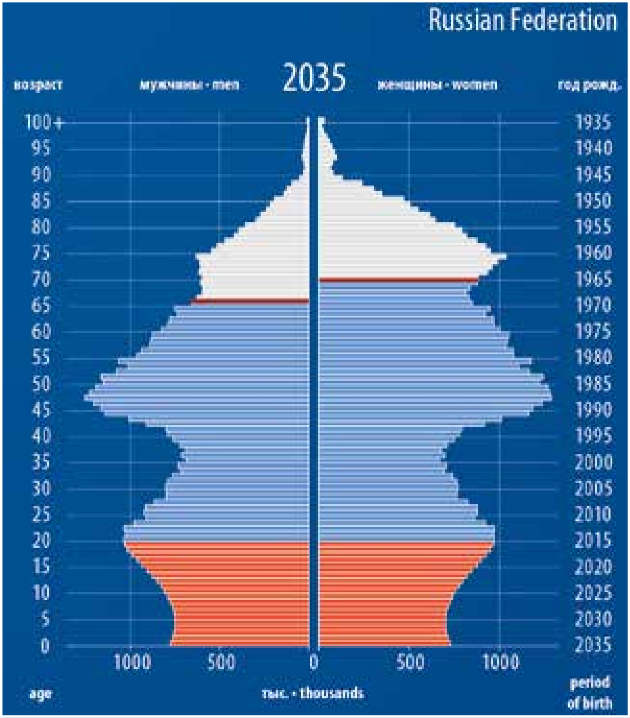
Moving Frontiers in Population Forecasting and Aging

Sergei Scherbov 65

Annotated Reprints of Key Publications



International Institute for Applied Systems Analysis
IIASA
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Wittgenstein Centre
FOR DEMOGRAPHY AND
GLOBAL HUMAN CAPITAL

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International Institute for Applied Systems Analysis (IIASA)

Founded in 1972, IIASA is an international scientific institute that conducts policy-oriented research into problems that are too large or too complex to be solved by a single country or academic discipline. Problems such as climate change, energy security, population aging, and sustainable development, which have a global reach and can be resolved only by international cooperation.

IIASA has a demonstrated track record of delivering global, regional, and national impact through conducting excellent interdisciplinary research into real-world problems, often in collaboration with large international research networks, and working with policymakers to identify and assess possible solutions based on the results of that research. Funded by prestigious research funding agencies in Africa, the Americas, Asia, Europe, and Oceania, IIASA is independent and unconstrained by political or national self-interest.

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Vienna University of Economics and Business (WU)

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Wittgenstein Centre for Demography and Global Human Capital (IIASA, VID/ÖAW, WU)

The Wittgenstein Centre is a collaboration among the World Population Program of the International Institute for Applied Systems Analysis (IIASA), the Vienna Institute of Demography of the Austrian Academy of Sciences (VID/ÖAW), the Demography Group and the Research Institute on Human Capital and Development of the Vienna University of Economics and Business (WU).

Contents

Reprints

Reprints

Reprints

Reprints

Foreword

This is a book to honor our distinguished colleague, Sergei Scherbov. Although he has recently spent a lot of his time redefining age, nevertheless, reaching the chronological age of 65 is still widely viewed as a threshold worth celebrating. But only under the conventional old-age dependency ratio – which itself should be retired soon – he is now moving from the denominator to the numerator. But, with 65 being the new 55, he should still have many productive years ahead, and this volume is just an interim assessment of his work.

The volume includes reprints of some of Sergei's most important publications to date. It was a difficult choice: it was not easy to select the papers reprinted here out of his many times larger total *opus.* We tried to cluster those papers around six of his main research areas, some of which are concentrated within a few years, while others accompanied him throughout his entire scientific career. We invited senior scholars who have been working with Sergei on these issues to provide brief substantive introductions to those sets of reprints. First and foremost, his work has dealt with population forecasting. There were so many important contributions to that field that we decided to split it into probabilistic population forecasts (with an introduction by Wolfgang Lutz) and long-term scenario analysis (with an introduction by Brian O'Neill). Next there is a section on Sergei's current preoccupation with redefining age and aging (with an introduction by Warren Sanderson and Stefanie Andruchowitz). Another section bundles contributions on directly policy-relevant topics and models relating population and the environment which were spread over quite some years (with an introduction by Alexia Fürnkranz-Prskawetz). While all of his work was based on solid demographic methods, some papers had an explicitly methodological focus and form a separate cluster (with an introduction by Frans Willekens). Finally, in the very recent past, Sergei has again strengthened his links to Russia, in a way coming back to important work he did over 30 years ago before joining IIASA. That is why we entitled this section "Back to Russian Roots" (with an introduction by Serhii Pyrozhkov).

We hope that both his demographer colleagues and the next generation of international demographers, will find this impressive set of his papers a useful substantive summary of not only the impressive work of one scholar but also of the epistemological development of an important strain of formal demography with highly relevant applications.

Sergei's papers reprinted here span 34 years, from 1983 to 2017. We hope to publish an update in another 34 years when his chronological age will be 99; however, considering changes in life expectancy and the lower mortality of scholars, his prospective age will be more like 80.

Wolfgang Lutz, Warren C. Sanderson, and Stefanie Andruchowitz

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1 Probabilistic Population Forecasts

Introduction

Wolfgang Lutz

"Forecasting is one of the oldest of demographic activities, and yet it has never been fully integrated with the main body of demographic theory and data. The fact that the public regards it as our most important task finds no reflection in our research agenda." This statement by Nathan Keyfitz still holds as true today as it did back in 1994 when it was written (Keyfitz 1994), but it has never applied to Sergei Scherbov. Population forecasting has been Sergei's most central professional concern from his first writings on global modeling while he was still in Moscow to his most recent publications that bring the newly defined measures of age and aging into the context of forecasting.

In terms of his publications, the papers dealing with forecasting present such a rich and broad set that in the context of this volume of reprints, we have decided to split it into two parts: the work on probabilistic forecasting and the work on long-term scenarios. Both sets of papers have in common that they explicitly deal with uncertainty in future population trends. Since all these components of population change, fertility, mortality, and migration are unknowns in terms of their future trends, the future of population trends is clearly indeterminate. But we know more than nothing about the future. An analysis of past time series of the three demographic components shows that the most influential one, fertility, changes only slowly and along the general trajectory of demographic transition. Birth rates do not decline from more than six children to around two within a year or two. It is instead a slow process of social change that tends to take at least a decade, but mostly longer. Mortality is asymmetric in its variability: short-term mortality crises due to diseases, wars, or disasters can greatly increase within a short period, but a sustainable decline of general mortality levels is a slow and gradual process. Migration rates are clearly the most volatile of the three components; they can rise and fall due to short-term changes in the political environment. But even rather radical changes in one of these three components (the flow variables) take several decades to change the inert stock of population size and composition: this is because the average life span in most countries today is around 70-80 years. This makes population trends much more predictable, even decades into the future, than virtually all other social and economic trends.

When Sergei entered the field of population forecasting in the 1980s the dominant approach used by the United Nations and virtually all national statistical agencies was to produce a medium variant together with high and low variants; that, in case of the UN, assumed fertility rates that were half a child higher or lower than in the medium variant, which was also considered the most likely. While the publication of high and low variants does convey some notion of uncertainty in future trends, nobody really knows how to interpret them statistically. Are they assumed to give the maximum range possible under still plausible assumptions (which extreme scenarios often try to do) or are they supposed to cover a certain uncertainty range of 50, 80, or 95 percent of possible future trajectories? This question has never been answered in a satisfactory way by those who produce such variants. The interpretation is further complicated by the fact that typically only alternative fertility assumptions are being used, while uncertainty in future mortality and migration is not covered; moreover, the high and low assumptions are applied simultaneously to all countries, thus assuming an unrealistic perfect correlation among the national trends of all the countries of the world.

This clearly unsatisfactory state of affairs in population forecasting was the starting point for Sergei's work on probabilistic population projections. In our 1994 IIASA volume entitled "The future population of the world: What can we assume to day?" (Lutz 1994) we presented projection results in terms of a cross-classification of high, medium, and low assumptions (each assumed to cover roughly 80 percent of the symmetric future uncertainty range of that component, as defined and justified by distinguished experts in the field) for all three components and for all world regions. While this approach clearly avoided some of the above-mentioned problems, it presented the users with a huge matrix of results from which they could form their own preferred aggregate scenarios. When it came to updating these scenarios in 1996, I remember well how Sergei, Warren, and I were looking at the graph of total population sizes that resulted from these 27 scenarios for each world region. The different lines were much closer to each other near the center as given by the combination of the three medium assumptions and spread more thinly towards the margin. Then one of us said, "This looks like a normal distribution; why not model it through normal distributions instead of discrete scenarios?" We simply decided to fit normal distributions through the high-medium-low ranges of the given fertility, mortality, and migration assumptions in such a way that they corresponded to the 80 percent range of normal distributions. We still had to make some assumptions on correlations, and then Sergei went home in the evening and did not go to bed but – in his usual way – sat next to his computer for most of the night and essentially programmed his existing projection software to run a thousand independent projections, each one randomly picking from the given distributions of future fertility, mortality, and migration trends. When Sergei showed us a graph with the distribution of results, we were actually looking at the first-ever probabilistic global population forecasts.

What followed was a quite unusual career for a rather technical demographic piece of research. It was published in the papers of *Nature*, the world's leading interdisciplinary scientific journal. This new approach for analytically dealing with the future number of human beings on our planet caught such broad interdisciplinary attention that even the two subsequent updates of these projections with newer data and some further methodological improvements were also accepted for publication in *Nature.* The substantive focus of these three papers – which are all reprinted in this volume together with their appendices – clearly shows the changing concerns about population-related challenges. The first paper published in 1997 was entitled "Doubling of world population unlikely" (Lutz, Sanderson, et al. 1997, this volume). This was at a time when most experts, as well as the public media, talked about a further doubling as a near certainty. But since our projections were a bit lower than those of the UN and the base year population kept increasing, our uncertainty range showed that there was exactly a two-thirds (67 percent) chance that by 2100 world population would level off before reaching 11.6 billion (i.e., double that of the 1995 base line of 5.8 billion). The new update published in 2001 was then entitled "The end of world population growth" (Lutz et al. 2001, this volume). The update showed that according to our projections, there was a high chance of over 80 percent that world population would level off before the end of the 21st century. Given that this was right at the beginning of the new century and the possible population explosion was still on the minds of many people as one of the top contemporary concerns, this paper received enormous media coverage by newspapers in almost every corner of the planet. It was widely interpreted as very good news for our global future.

The third in the series of *Nature* papers updated our global projections in 2008 then looked at the other side of the coin of fertility decline. It was entitled "The coming acceleration of global population ageing" (Lutz et al. 2008, this volume). The paper demonstrated under a probabilistic framework that that for a large number of aging indicators at the global level and for most regions the period after 2020 will see an acceleration in the speed of aging. This paper already used some of the new aging indicators that consider changes in remaining life expectancy, a line of research by Sergei and Warren that will be documented in Section 3 of this volume. A final update using the same approach of expert-based probabilistic population projections on the basis of 12 world regions was published in 2011 in *Population and Development Review* on the topic of "The uncertain timing of reaching 8 billion, peak world population and other demographic milestones" (Scherbov et al. 2011, this volume). It focused on the controversy about when exactly the mark of 7 billion people would be reached, a date that the UN had set at 31 October 2011. In this paper, we also used the methodological innovation of factoring into the model some uncertainty about base line data in population counts as well as vital rates.

Sergei and I also produced a set of national probabilistic population projections for a number of countries, mostly in collaboration with national statistical institutes. Unlike more recent probabilistic projections which are based on Bayesian models and take information from all other countries into account, this expert-based probabilistic model was directly applicable to the way in which national statistical offices do their own projections to this very day. All that was required was to take the national expert-based alternative assumptions on fertility, mortality, and migration and add just distributional assumptions. Such projections have found their way into the "official" projections of Austria (Lutz, Scherbov, et al. 1997, this volume) and were also used in a high-level process on demographic change conducted by the German Parliament in 1996-98. Actually, Sergei's probabilistic age pyramid for Germany in 2030 made it on to the cover of the 880-page volume resulting from this broad demographic assessment of the newly united Germany (Deutscher Bundestag 1998).

More recently, the international population forecasting activities at IIASA have shifted into the direction of adding educational attainment systematically as an explicit third demographic dimension to age and sex. As fertility and mortality tend to systematically vary with level of education, and changes in the educational attainment distributions of populations are of great importance for the social and economic consequences of demographic change, this has widely been considered as another important innovation in the field of forecasting. It has been convincingly demonstrated that education is to be considered as the single most important source of observable population heterogeneity after age and sex. Methodologically, this goes back to Sergei's early years at IIASA when he was among the pioneers of multi-state demography and in particular focused on the computational side, as will be described in Section 5 by Frans Willekens. Yet many people have asked us, and we have asked ourselves several times, whether these two innovations in different directions (multi-state versus probabilistic) cannot be combined in a unified framework. This is no easy task because multi-state projections involve many more parameters for which probabilistic assumptions will have to be made. However, Sergei did not stop thinking about all the problems involved, and he actually calculated such a model for the case of India in a paper entitled "Probabilistic population projections for India with explicit consideration of the fertility-education link" published in the *International Statistical Review* 2004 (Lutz & Scherbov 2004, this volume). The issue of combining both approaches clearly remains on our agenda for the future and this paper may show in which direction to go.

Finally, one of the major drawbacks of probabilistic population projections is that they cannot really be used for policy analysis, e.g. the questions: What would be the consequence on population growth of a strong government effort in reducing child mortality as compared to no such effort. While such policy-related forecasts can readily be produced under a framework of alternative scenarios, fully probabilistic forecasts do not offer such conditional analyses because the future pathways are assumed to be entirely exogenously determined and the effects of all possible future policies are somehow assumed to be already included in the uncertainty distributions. This is also one of the major points of criticism from the perspective of users about the recent shift of the UN World population projections to fully probabilistic projections. This lack of policy-related analysis is probably also the reason why the UN still continues to publish its high and low variants, although statistically these two approaches are quite inconsistent and the high-low range is far larger than the probabilistic 95-percent interval at the global level, mostly due to different correlation assumptions (Abel et al. 2016). Here, another paper by Sergei (together with Warren, Brian and myself - Sanderson et al. 2004, this volume) offers an attractive solution to this problem. The concept of conditional probabilistic forecasting combines the benefits of probabilistic uncertainty intervals with the possibility of conditioning on the assumed consequences of certain policies. If one, for example, assumes that government policies would result in a TFR that is 0.5 lower (as the UN low variant does) then the model could still combine this with the full mortality and migration uncertainty. Although published in 2004, the idea has not yet been picked up by the UN, although it would offer an elegant way of combining policy-relevant projections with probabilistic projections.

These last two papers reprinted here contain the blueprints for further important contributions that will make probabilistic population projections better and more useful. The world must hope for many more productive years on the part of Sergei so that he can also crack these difficult nuts.

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Doubling of World Population Unlikely[1]

Wolfgang Lutz, Warren C. Sanderson and Sergei Scherbov

Most national and international agencies producing population projections avoid addressing explicitly the issue of uncertainty. Typically, they provide either a single projection or a set of low, medium and high variants (United Nations 1992; United Nations 1995), and only very rarely do they give these projections a probabilistic interpretation. Probabilistic population projections have been developed for specific industrialized countries, mostly the United States, and are based largely on time-series analysis (Lee 1992). On a global level, time-series analysis is not applicable because there is a lack of appropriate data, and for conceptual reasons such as the structural discontinuity caused by the demographic transition (Alho 1997; Lutz et al. 1996; Nordhaus 1994). Here we report on a new probabilistic approach that makes use of expert opinion on trends in fertility, mortality and migration, and on the 90 per cent uncertainty range of those trends in different parts of the world. We have used simulation techniques to derive probability distributions of population sizes and age structures for 13 regions of the world up to the year 2100. Among other things, we find that there is a probability of two-thirds that the world's population will not double in the twenty-first century.

The probabilistic projections are based on distributions for fertility, mortality and migration in all regions, defined in terms of high or low values assumed to cover 90 per cent of all possible future outcomes. For today's high-fertility countries they are based on an assessment of their current standing in the process of demographic transition towards low fertility (Cleland 1996), together with information about reproductive intentions (Westoff 1996). These data show that even in sub-Saharan Africa the fertility transition has started, and that it is well advanced in most other developing regions. The high and low assumptions for the years 2030-2035 are total fertility rates (TFR, the number of children per woman) of 4.0 and 2.0 in Africa, central Asia and the Middle East, 3.0 and 1.7 in southern Asia, Pacific Asia and Latin America and 3.0 and 1.5 in Central East Asia (mostly China).

For today's industrialized countries the assumptions are based on a broad survey of possible future societal changes (Lutz 1996a). The United Nations and other institutions have assumed that fertility will eventually recover to replacement level (TFR slightly above 2.0), but there is little support for this view (Keyfitz 1991; Westoff & Lutz 1991). Accordingly, TFR values of 2.1 and 1.3 for Europe and the Pacific members of the Organization for Economic Cooperation and Development (OECD countries) and 2.3 and 1.4 for North America have been assumed for 2030-2035.

Assumptions for mortality were set in terms of increase in life expectancy at birth per decade. Contrary to earlier beliefs, there now is a considerable degree of uncertainty about the future course of mortality. In the industrialized countries this stems from the scientific dispute of whether we are already close to a biologically determined limit to life expectancy (Vaupel & Lundström 1996; Manton 1991). Accordingly, increases of 3.0 and 1.0 years have been assumed as the 90 per cent range. In the developing countries the uncertainty is more associated with future trends in AIDS (Bongaarts 1996) and other infectious diseases and the development of health services (Garenne & Lutz 1996). For certain regions possible problems with food supply have also been considered (Cohen 1995; Heilig 1996).

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Consequently in such cases the assumed range of mortality improvement is wide, for example +4.0 to -2.0 years per decade in sub-Saharan Africa.

Migration is most difficult to handle because of unreliable data and high volatility (Zlotnik 1996, p.199). For this study a matrix of constant annual interregional migration flows was assumed with the 90 per cent ranges covering two million to zero migration gains in North America, and l million to zero in Western Europe.

Table 1. Result of probabilistic projections for 13 world regions

	Total population (millions)				Population above age 60 (in %)			
		2050				2050		
Region	1995	Median	2.5%*	97.5%*	1995	Median	2.5%*	97.5%*
Africa								
North Africa	162	439	309	583	5.9	13.3	9.4	19.2
Sub-Saharan Africa	558	1,605	1,085	2,316	4.7	9.2	6.9	12.8
East Asia								
Central East Asia	1,362	1,865	1,351	2,574	9.2	24.9	17.8	34.1
Pacific Asia	447	796	579	1,047	6.8	19.4	14.4	26.5
Pacific OECD countries	147	146	117	182	19.4	39.5	31.5	48.7
West Asia								
Central Asia	54	137	88	206	7.8	15.4	10.2	24
Middle East	151	515	380	692	5.4	12.5	9.1	17.3
Southern Asia	1,240	2,368	1,833	2,970	6.7	16.6	13.4	20.8
Europe								
Eastern Europe	122	110	86	141	16.7	34	26.7	43.4
Former Soviet Union (European part)	238	188	144	241	16.9	34.1	26.3	44.5
Western Europe	447	471	370	584	18.6	35	27.5	43.9
Latin America	477	925	707	1,177	7.6	20.4	15.8	26.4
North America	297	403	303	534	16.4	30.2	24	38.6

Fertility, mortality and migration are assumed to be independent.

*Columns labelled 2.5% and 97.5% provide data on the lower and upper bounds, respectively, of the 95 per cent confidence interval.

The projections for 13 regions (see Table 1) show that population growth will probably be most rapid in the middle East, sub-Saharan Africa and North Africa, with a tripling of the population by 2050 and a quadrupling by 2100 likely. Despite this rapid growth, there will also be significant increases in the proportion above 60 years of age. In contrast, in Eastern Europe and the European part of the former Soviet Union, population will probably decrease over the coming decades. By 2050 the Pacific OECD countries and Western Europe are likely to experience little, if any, change in population size. This stagnation or shrinkage in population size in Europe and the Pacific OECD countries will be associated with significant ageing of the population, with the proportion above 60 likely to double from its current values. Even proportions well above 40 per cent are within the 95 per cent confidence interval. These could bring serious consequences for social security systems.

In North America, a younger age distribution, a larger inflow of migrants, and slightly higher fertility than in Europe is likely to result in a roughly 25 per cent increase in population by 2050. Population ageing will occur, but will not be as dramatic as in Europe. Latin America is likely to have a doubling of its population and an increase in its proportion above age 60 to about 20 per cent. By 2050, Central East Asia (mostly China) is likely to grow by 37 per cent and experience an increase in the proportion over 60 from 9 per cent to 25 per cent. Southern Asia (essentially the Indian subcontinent), which still has relatively high fertility and a young population, will probably double its population by 2050 and will be the world's most populous region.

The global results for population size are presented in Fig. 1; those for the proportion above 60 years of age are shown in Fig. 2. The median path of world population growth will increase from 5.8 billion today to 7.9 billion in 2020 and 10.0 billion in 2050. It will reach a peak around 2070-2080, and then begin a slow decline. In 2020 the range of uncertainty of this projection will be rather narrow (with the 95 per cent confidence interval between 7.5 billion and 8.3 billion) because many of the people who will be alive at that date have already been born. By 2050, the 95 per cent confidence interval will widen to between 8.1 billion and 11.9 billion, but the most likely 60 per cent (medium and dark shaded area in Fig. 1) still covers a range of less than one billion. After 2050 the size of the 95 per cent confidence interval will increase substantially, with the 60 per cent confidence interval

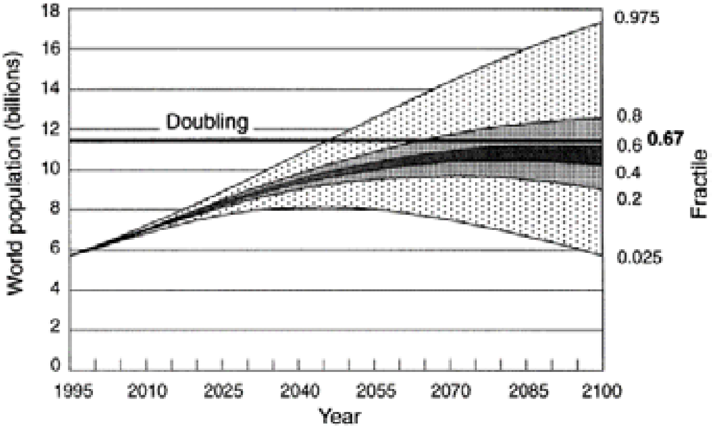

Figure 1. Fractiles of the probability distribution of the future size of the world population.

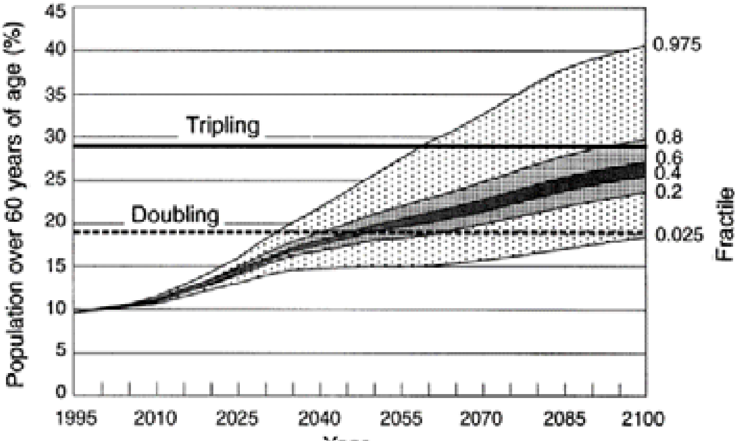

Figure 2. Fractiles of the probability distribution of the proportion of the world population above 60 years of age.

showing a much smaller rise. The proportion of the world's population above age 60 is likely to increase from 9.5 per cent today to 20 per cent in 2050 to 27 per cent by 2100. A strong increase in the proportion of elderly people is virtually certain, with the low end of the 95 per cent confidence interval showing almost a doubling of today's level.

These probabilistic projections lead us to believe that the focus of public, political and scientific concern will continue to shift from global population growth to population ageing.

Methods

The probabilistic population projections are based on the multistate cohort component model of population projections, which applies assumed agespecific fertility, mortality and migration rates to the age and sex distribution of the starting population along cohort lines (Keyfitz 1977; Rogers 1975). A group of demographers have analysed trends in fertility, mortality and migration in different parts of the world (Lutz 1996b). Their discussions produced a consensus about ranges in 2030-2035 that they thought would cover 90 per cent of all future paths of TFR, life expectancy at birth, and the interregional migration matrix (Lutz 1995). Because the resulting distribution s of assumed values turned out to be symmetric, normal distributions were fitted to those ranges. For each of the three variables, a single draw from a standard normal distribution determined its relative position within its range of future values at selected dates. The values at intermediate dates were determined by piece-wise linear interpolation. This method has been labelled a random scenario approach to population projection (Lee 1999). Experiments with less autocorrelated paths for each variable produced very similar means and medians and minor differences in variances (Lutz & Scherbov 1997).

Beyond 2030-2035, fertility was assumed to reach an average level of between 1.7 and 2.1 children per woman by 2080, with the specific value depending on population density in 2030 (the high the density, the lower the fertility). The 90 per cent range around that value was set at 1.0 children. The range for life-expectancy increases after 2030-2035 was set to 0-2.0 years per decade. Smooth transitions of assumed future life expectancies at birth into age-specific mortality rates were performed by transforming baseline mortality patterns with the help of relational models (Brass 1971). Because separate baseline data were needed for males and females in each region, 26 patterns were used. Agespecific fertility rates were derived from the total fertility rates by using a fixed relative age profile of fertility. We used a fixed relative age profile for migrants to determine age-specific migration rates. The projections were performed in fiveyear steps on populations in five-year age groups.

An unusual feature of this global projection is the explicit consideration of possible correlations in fertility and mortality between and within regions. Four sets of 1,000 simulations were produced, resulting from a cross-classification of perfectly correlated/ uncorrelated fertility and mortality trends across regions and within regions. The regional results presented in Table 1 are from the set with uncorrelated trends. The global results are based on the merged distribution of all four sets of simulations, which make up 4,000 projections in total.

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The End of World Population Growth[1]

Wolfgang Lutz, Warren C. Sanderson and Sergei Scherbov

There has been enormous concern about the consequences of human population growth for the environment and for social and economic development. But this growth is likely to come to an end in the foreseeable future Improving on earlier methods of probabilistic forecasting (Lutz et al. 1997), here we show that there is around an 85 per cent chance that the world's population will stop growing before the end of the century There is a 60 per cent probability that the world's population will not exceed 10 billion people before 2100, and around a 15 per cent probability that the world's population at the end of the century will be lower than it is today For different regions, the date and size of the peak population will vary considerably.

Figure 1 shows the probability that the world population size would reach a peak at or before any given year. It indicates that there is around a 20 per cent chance that the peak population would be reached by 2050, around a 55 per cent chance that it would be reached by 2075, and around an 85 per cent chance that it would be reached by the end of the century.

There is around a 75 per cent chance that the peak population of the European portion of the former USSR has already been reached in 2000, an 88 per cent probability that it will be reached by 2025, and over a 95 per cent chance by the end of the century. For the China region, the probability of reaching a peak within the next two decades is still low owing to its relatively young age structure. By 2040 the probability becomes greater than half. In sub-Saharan Africa, despite the prevalence of HIV, there is a low probability of peaking before the middle of the century. The probability reaches 25 per cent by 2070, 50 per cent by 2085, and almost 75 per cent by 2100, owing to assumed reductions in fertility.

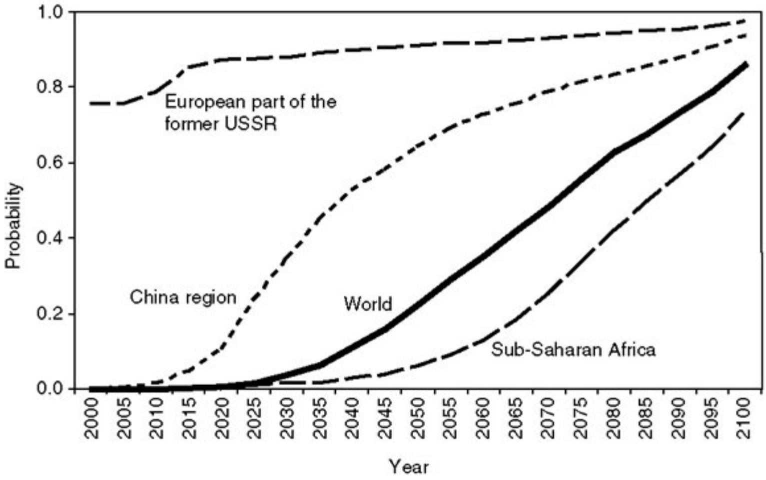

Figure 1. Forecasted probability that population will start to decline at or before the indicated date.

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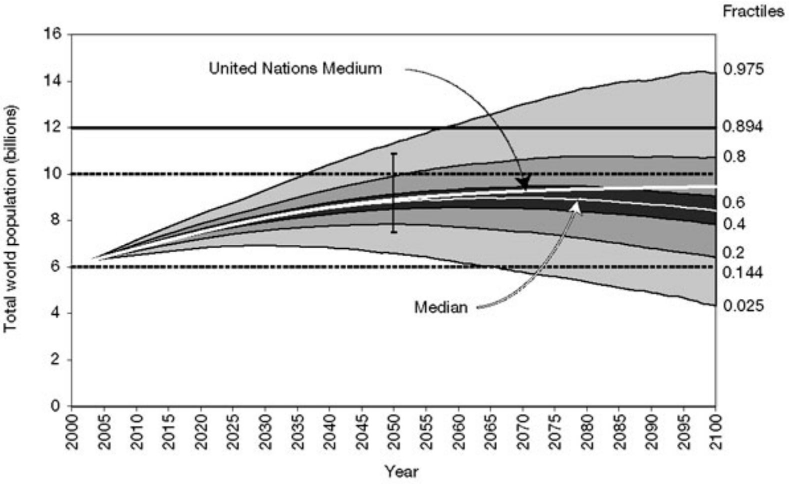


Figure 2. Forecasted distributions of world population sizes (fractiles). For comparison, the United Nations medium scenario (white line), and 95 per cent interval as given by the NRC11 on the basis of an ex post error analysis (vertical line in 2050) are also given.

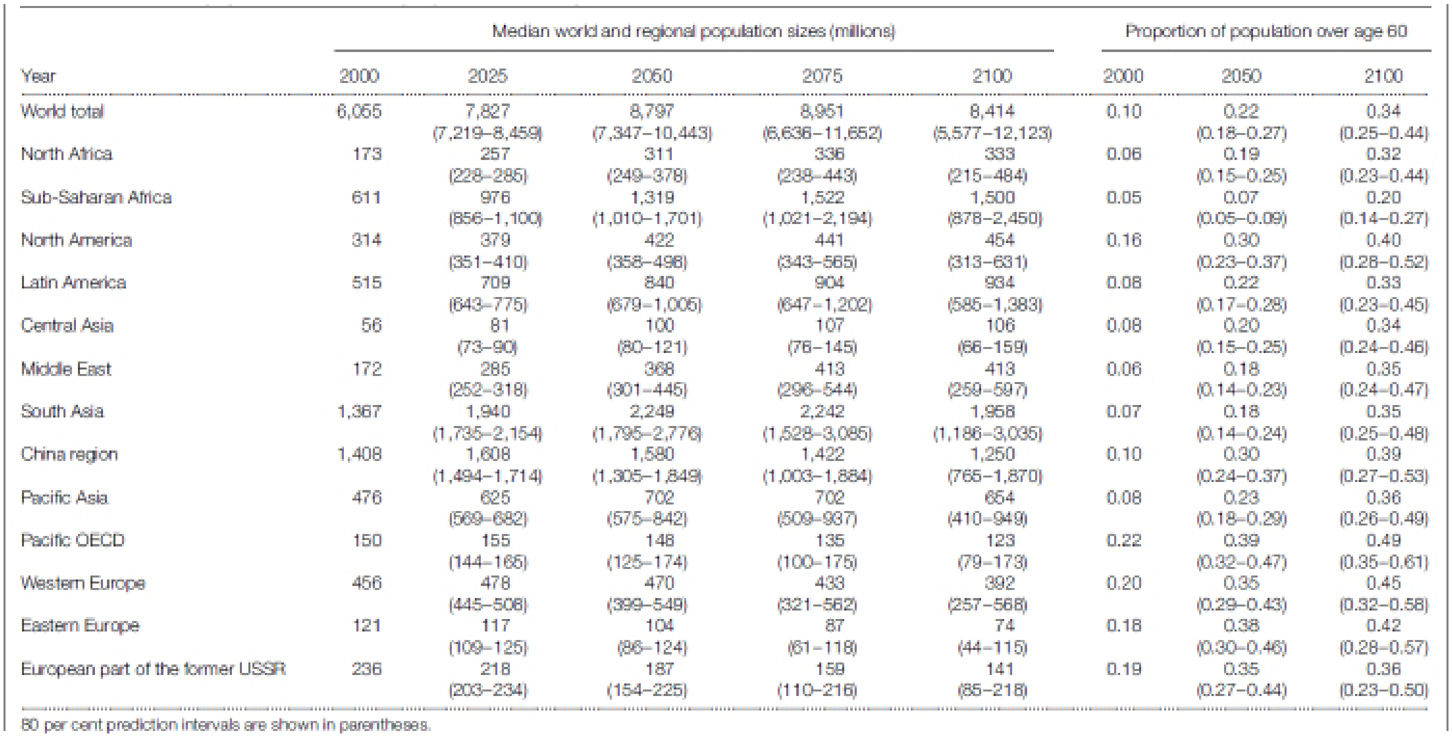
Figure 2 shows the distribution of simulated world population sizes over time. The median value of our projections reaches a peak around 2070 at 9.0 billion people and then slowly decreases. In 2100, the median value of our projections is 8.4 billion people with the 80 per cent prediction interval bounded by 5.6 and 12.1 billion. The medium scenario of the most recent United Nations long-range projection (United Nations 1999) is inserted in Figure 2 as a white line. It is almost identical to our median until the middle of the century, but is higher thereafter owing to the United Nations assumption of universal replacement-level fertility, that is two surviving children per woman.

Table 1 shows the median population sizes and associated 80 per cent prediction intervals for the world and its 13 regions, indicating major regional differences in the paths of population growth. While over the next two decades the medians are already declining in eastern Europe and the European portion of the former Soviet Union, the populations of north Africa and sub-Saharan Africa are likely to double, even when we take into account the uncertainty about future HIV trends.

The China region and the South Asia region, which have approximately the same population size in 2000, are likely to follow very different trends. Owing to an earlier fertility decline, the China region is likely to have around 700 million fewer people than the South Asia region by the middle of the century. This absolute difference in population size is likely to be maintained over the entire second half of the century and illustrates the strong impact of the timing of fertility decline on eventual population size (O'Neill et al. 1999).

Our findings concerning the timing of the end of world population growth are robust to plausible changes in parameter assumptions. A detailed sensitivity analysis is provided as Supplementary Information. The forecasts of the World Bank, the US Census Bureau, and the medium variant of the United Nations (US Census Bureau 2000; United Nations 1999; World Bank 2000) are based on independent assumptions; the median trajectory of our world forecasts is almost identical to these up until 2045. Of these three forecasts, only

Table 1. Forecasted population sizes and proportions over age 60



	Median world and regional population sizes (millions)					Proportion of population over age 60		
Year	2000	2025	2050	2075	2100	2000	2050	2100
World total	6,055	7,827 (7,219–8,459)	8,797 (7,347–10,443)	8,951 (6,636–11,652)	8,414 (5,577–12,123)	0.10	0.22 (0.18–0.27)	0.34 (0.25–0.44)
North Africa	173	257 (228–285)	311 (249–378)	336 (238–443)	333 (215–484)	0.06	0.19 (0.15–0.25)	0.32 (0.23–0.44)
Sub-Saharan Africa	611	976 (856–1,100)	1,319 (1,010–1,701)	1,522 (1,021–2,194)	1,500 (878–2,450)	0.05	0.07 (0.05–0.09)	0.20 (0.14–0.27)
North America	314	379 (351–410)	422 (358–498)	441 (343–565)	454 (313–631)	0.16	0.30 (0.23–0.37)	0.40 (0.28–0.52)
Latin America	515	709 (643–775)	840 (679–1,005)	904 (647–1,202)	934 (585–1,383)	0.08	0.22 (0.17–0.28)	0.33 (0.23–0.45)
Central Asia	56	81 (73–90)	100 (80–121)	107 (76–145)	106 (66–159)	0.08	0.20 (0.15–0.25)	0.34 (0.24–0.46)
Middle East	172	285 (252–318)	368 (301–445)	413 (296–544)	413 (259–597)	0.06	0.18 (0.14–0.23)	0.35 (0.24–0.47)
South Asia	1,367	1,940 (1,735–2,154)	2,249 (1,795–2,776)	2,242 (1,528–3,085)	1,958 (1,186–3,035)	0.07	0.18 (0.14–0.24)	0.35 (0.25–0.48)
China region	1,408	1,608 (1,494–1,714)	1,580 (1,305–1,849)	1,422 (1,003–1,884)	1,250 (765–1,870)	0.10	0.30 (0.24–0.37)	0.39 (0.27–0.53)
Pacific Asia	476	625 (569–682)	702 (575–842)	702 (509–937)	654 (410–949)	0.08	0.23 (0.18–0.29)	0.36 (0.26–0.49)
Pacific OECD	150	155 (144–165)	148 (125–174)	135 (100–175)	123 (79–173)	0.22	0.39 (0.32–0.47)	0.49 (0.35–0.61)
Western Europe	456	478 (445–508)	470 (399–549)	433 (321–562)	392 (257–568)	0.20	0.35 (0.29–0.43)	0.45 (0.32–0.58)
Eastern Europe	121	117 (109–125)	104 (86–124)	87 (61–118)	74 (44–115)	0.18	0.38 (0.30–0.46)	0.42 (0.28–0.57)
European part of the former USSR	236	218 (203–234)	187 (154–225)	159 (110–216)	141 (85–218)	0.19	0.35 (0.27–0.44)	0.36 (0.23–0.50)

80 per cent prediction intervals are shown in parentheses.

the UN long-range projections provide scenarios of the world's population to the end of the century. If we define the end of population growth slightly less literally, and take it to correspond with annual population growth of one-tenth of one per cent or less, the United Nations medium projection also shows the end of population growth during the second half of the century. Their medium scenario predicts that world population growth will first fall below one-tenth of one per cent at around 2075.

A stabilized or shrinking population will be a much older population. At the global level the proportion above age 60 is likely to increase from its current level of 10 per cent to around 22 per cent in 2050. This is higher than it is in western Europe today. By the end of the century it will increase to around 34 per cent, and extensive population ageing will occur in all world regions. The most extreme levels will be reached in the Pacific OECD (mostly Japan), where half of the population is likely to be age 60 and above by the end of the century, with the 80 per cent uncertainty interval reaching from 35 to 61 per cent. Even sub-Saharan Africa in 100 years is likely to be more aged than Europe today. The trend of our median proportion over age 60 is almost identical to that of the UN long-range projections (United Nations 1999) up to 2050, but shows significantly stronger ageing thereafter. This confirms recent criticism that conventional projections tend to underestimate ageing (Tuljapurkar et al. 2000; Vaupel & Lundström 1996). The extent of and regional differences in the speed of population ageing – the inevitable consequence of population stabilization and decline – will pose major social and economic challenges.

However, population numbers are only one aspect of human impact, and in some of the world's most vulnerable regions, significant population growth is still to be expected. Nevertheless, the prospect of an end to world population growth is welcome news for efforts towards sustainable development.

Methods

The method of probabilistic population projection that was applied here (see Box 1) is a further development of our earlier approach (Lutz et al. 1996; Lutz et al. 1997; Lutz et al. 1999) that allows short-term fluctuations in the vital rates (Lee 1999; Tuljapurkar et al. 2000) and refers to the ex post error analysis of past projections (National Research Council 2000). We produced a set of 2000 simulations by single years of age for 13 world regions (Lee & Tuljapurkar 1994) starting in 2000. Information on baseline conditions has been derived from the United Nations (United Nations 1999) and US Census Bureau (US Census Bureau 2000) estimates, and the sensitivity of our results to possible baseline errors is discussed in the Supplementary Information. World population sizes at five-year intervals for all 2000 simulations are also listed there.

The substantive assumptions about future trends in the three components of fertility, mortality and migration, and their associated uncertainty ranges are based on revisions and updates of our earlier work (Lutz 1996) and the extensive analyses summarized in the recent US National Research Council (NRC) report (National Research Council 2000).

Fertility

The key determinant of the timing of the peak in population size is the assumed speed of fertility decline in the parts of the world that still have higher fertility. On this issue there is a broad consensus that fertility transitions are likely to be completed in the next few decades (National Research Council 2000). For the eventual size of the population and the question of whether or not world population will begin a decline by the end of this century the key variable is the assumed level of post-transitional fertility. The thorough review of

Box 1

Different approaches to probabilistic population projections

The cohort component method of projection is taken as a standard; thus, the differences between alternative approaches discussed in this box refer only to the modelling of future fertility, mortality and migration rates. Here we can distinguish between the specific process chosen for representing the time series of rates, and the basis for the specific assumptions made about the future range of uncertainty.

Model

In the literature there are essentially two methods of specifying the series of vital rates: (1) processes with annual fluctuations (Alho 1990; Lee 1999; Lee & Carter 1992; Lee & Tuljapurkar 1994); and (2) piece-wise linear scenarios (Lutz et al. 1996; Lutz et al. 1997; Lutz & Scherbov 1998). Whereas method (2) has the advantage of conforming to the current practice of scenario definition in statistical offices around the world (including the UN) (United Nations 1999), method (1) can produce realistic annual fluctuations given that the possible levels are bounded. We have chosen the following moving-average model with annual fluctuations, in order to avoid the argument that our model underestimates variance (Lee 1999).

Let v be a vital rate to be forecasted for periods 1 through T and v_t the forecasted value at time t. $v_t = \bar{v_t} + \varepsilon_t$, where the mean of v, $\bar{v_t}$, and its standard deviation at t, $\sigma(\varepsilon_t)$, are determined according to the assumptions in the text. Let $\{x_{2-n}, \cdots, x_T\}$ be the values of $T + n - 1$ independent draws from a standard normal distribution and n be the number of periods in the moving average. Then $\varepsilon_t = \frac{\sigma(\varepsilon_t)}{\sqrt{n}} \cdot \sum_{i=t-n+1}^{t} x_i$.

A more detailed description of the model is given in the Supplementary Information.

Assumptions

The literature suggests three approaches for deriving assumptions about the future range of uncertainty of the components: (1) to compute a measure of the future error from the ex post analysis of past projections (Alho 1997; Keilman 1999; Stoto 1983); (2) to apply time series models (Lee 1999; Lee & Tuljapurkar 1994); and (3) to have well-informed experts make assumptions based on explicitly stated substantive arguments (Lutz et al. 1999). These three approaches are not mutually exclusive, and approaches (1) and (2) also include expert judgement.

Here we use a synthesis of the three approaches. Our process specification uses a time series model. We have explicitly considered existing national-level parameter estimates (Lee & Carter 1992; Lee & Tuljapurkar 1994) given that, at the level of world regions, empirical estimation is impossible owing to lack of data. The ex post analysis of past errors enters our study in two ways: the substantive assumptions made on fertility and mortality changes are informed by the analysis of past errors in those components (National Research Council 2000; Keilman 1999), and our results at the regional level have been compared to the results of an ex post error analysis of global UN projections documented in the NRC report. Because we preferred to err on the side of higher variance (that is, lower probability of population growth ending this century), we followed the general rule of producing intervals that are at least as large as those in the NRC report at the level of major world regions (National Research Council 2000).

Combining this with argument-based expert judgement (Lutz 1996), we saw substantive reasons for assuming a larger uncertainty in many regions as a result of new factors such as HIVIAIDS, the new situation in the former USSR and the indeterminacy of long-range post-transitional fertility levels that will affect an increasing number of countries.

The 95 per cent interval resulting from the NRC ex post error analysis is inserted in Figure 2 as a vertical line in 2050 (the latest year given in the NRC report). It corresponds to roughly 80 per cent of our distribution, which clearly indicates that our method produces a broader uncertainty range than the ex post error approach.

the literature on that subject by the NRC states that “fertility in countries that have not completed transition should eventually reach levels similar to those now observed in low fertility countries” (National Research Council 2000, p.106). Our fertility assumptions are consistent with this view.

The trends in the means of the regional fertility levels have been defined for the periods 2025-29 and 2080-84 with interpolations in between. The total fertility rates assumed for 2025-29 are similar to those chosen by the United Nations (United Nations 1999), but for 2080-84 they are assumed to range between 1.5 and 2.0, with lower levels for regions with higher population density in 2030. The variances in the total fertility rates are assumed to depend on the level of fertility. If the total fertility rate is above 3.0 there is an 80 per cent chance that fertility would be within one child of the mean. When it is below 2.0, the same probability is attached to a range within one half a child of the mean. Between the two total fertility rate levels, the variance is interpolated.

Life expectancy

We assume that life expectancy at birth will rise in all regions, except in sub-Saharan Africa, where HIV/AIDS will lower life expectancies during the early part of the century. In general, we assume that life expectancy increases by two years per decade with an 80 per cent probability that the increase is between zero and four years; but there are a number of exceptions to this rule based on specific regional conditions. These assumptions reflect the very large uncertainty that exists regarding future mortality conditions. On one hand, significant biomedical breakthroughs are likely to be made; on the other, AIDS could still become a major issue outside Africa, and new and unexpected threats to human life can emerge.

Autocorrelations

Migration is treated as a random vector on the basis of recent interregional migration patterns. The autocorrelation chosen for all components is based on a 31-year moving-average process that seemed the most plausible after we had experimented with 21-, 31-, and 41-year moving averages (see Supplementary Information), and is close to existing national level figures (Lee 1999). We assumed an interregional correlation of 0.7 for fertility and 0.9 for mortality deviations with no correlation between fertility and mortality deviations from the assumed trend, and perfect correlation between male and female life expectancy. These choices followed extensive sensitivity analyses as documented in the Supplementary Information. The main rationale behind our choice is that under post-transition conditions, correlations between deviations from assumed fertility and mortality trends are unlikely to be large, while globalization of communication is likely to bring correlated fluctuations of rates among world regions. Mortality correlations will be higher than fertility correlations, owing to the faster communication of medical technology and the faster spread of new health hazards. The sensitivity analysis documented in the Supplementary Information shows that our main conclusion, that there is around an 85 per cent chance that a peak in world population size will occur in this century, is quite robust to plausible changes in those correlations.

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Supplementary Information for "The End of World Population Growth"[1]

Wolfgang Lutz, Warren C. Sanderson and Sergei Scherbov

The central finding of this study is that there is a high probability that the world's population growth will come to an end in this century. In Section 1, we state the statistical model that we use. In Section 2, we discuss different possible correlations (autocorrelation, correlations between deviations in fertility and life expectancy and correlations across regions) and show the results of sensitivity analyses and their implications on our central finding. In Section 3 we deal with the issue of possible baseline errors in both the size of the starting population and the starting level of fertility.

1. The Statistical Model

It is accepted procedure to create population forecasts from an initial distribution of the population by age and sex and forecasts of total fertility rates (TFR), life expectancies at birth, and net migration. Probabilistic population forecasts differ from deterministic forecasts in that they deal with the uncertainty of the course of future rates and therefore must specify future total fertility rates, life expectancies, and net migration as distributions and not as points. Distributions can also be used to deal with other uncertainties such as those relating to the base population size.

In order to generate the required distributions, let v be the total fertility rate, the change in life expectancy at birth, or net migration to be forecasted for periods 1 through T and v_t be its forecasted value at time t. We express v_t as the sum of two terms, its mean at time t, $\overline{v_t}$ and its deviation from the mean at time t, ε_t. In other words, $v_t = \overline{v_t} + \varepsilon_t$. The $\overline{v_t}$ are chosen based on the arguments given in the text of the paper. The ε_t term is assumed to be a normally distributed random variable with mean zero and standard deviation $\sigma(\varepsilon_t)$. The $\sigma(\varepsilon_t)$ are also based on arguments in the text.

Because of the persistence of the factors represented by the ε_t, we would generally expect them to be autocorrelated. One of the most commonly used methods of specifying how the ε_t term evolves over time is the simple autoregressive formation (AR(1)), where $\varepsilon_t = \alpha \cdot \varepsilon_{t-1} + u_t$, where u_t is an independently distributed normal random variable with mean zero and standard deviation $\sigma(u)$. Another commonly used method is the moving average formation of order q, MA(q) where q is the number of lagged terms in the moving average. We use the following moving average specification:

$\varepsilon_t = \sum_{i-0}^{q} \alpha_i \cdot u_{t-i}$, where u_{t-i} are independently distributed standard normal random variables. To ensure that the standard deviation of ε_t is equal to its pre-specified value, we set the $\alpha_i = \frac{\sigma(\varepsilon_t)}{\sqrt{q+1}}$. Note that ε_t depends on $q+1$ random terms.

The choice between AR(1) and MA(q) does not have to do with estimation, but rather with representation. Data do not exist that would allow the estimation of the parameters of either specification at the regional level required in the paper. Neither is more theoretically correct than the other. Both are just approximations to a far more complex reality. When comparably parameterized, they produce very similar distributions of ε_t (see Figures 1 and 2).

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The choice between the two, therefore, rests on which more accurately reflects arguments concerning the future. From our perspective, the moving average approach has the advantage that the $\sigma(\varepsilon_t)$ terms appear explicitly making it easier to translate ideas about the future into that specification.

We generate correlated random numbers for each forecast year. Fertility and life expectancy change deviations (ε_t) from pre-specified mean paths can be correlated across regions or fertility and life expectancy change deviations can be correlated with one another within a region. Suppose that we were interested in R correlated states (regions or vital rates). Let $e_t(e_{t,1,} \dots, e_{t,R})$ be a column vector of the R autocorrelated values of e at time t generated as above, but under the assumption that $\sigma(e_{t,j,})$ is 1.0. Let V be the assumed variance-covariance matrix for the R states. We call the Cholesky decomposition of V, C. We compute a column vector $\varepsilon_t(\varepsilon_{t,1,} \dots, \varepsilon_{t,R})$ from the equation $\varepsilon_t = C' \cdot \varepsilon_t$.

2. Sensitivity Analysis of the Implications of Various Correlations

The future levels of vital rates that enter the simulations can be correlated in different ways. Most important are (a) the correlations between deviations from assumed average trends in fertility and life expectancy, (b) the autocorrelation of deviations within each series of vital rates and (c) the correlations among the deviations from the average vital rate trends in different world regions.

Since the assumed signs and degrees of correlations do influence the results to varying degrees it is important to explicitly address the issue and discuss the implications for the validity of our central findings.

2.a Correlations Between Fertility and Life Expectancy Deviations

In our earlier work (Lutz et al. 1996), we discussed the impact of two different intraregional correlations over time between fertility deviations and deviations in the change in life expectancy at birth on the assumption of zero correlation both between the deviations in

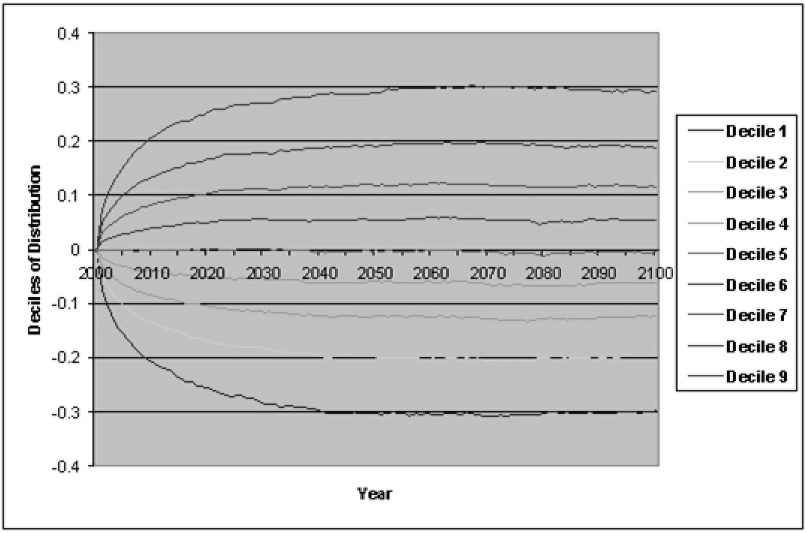

Figure 1. AR(1), α=0.9677, $\sigma(u)$=0.05896, $v(0)$=0, 10,000 simulations.

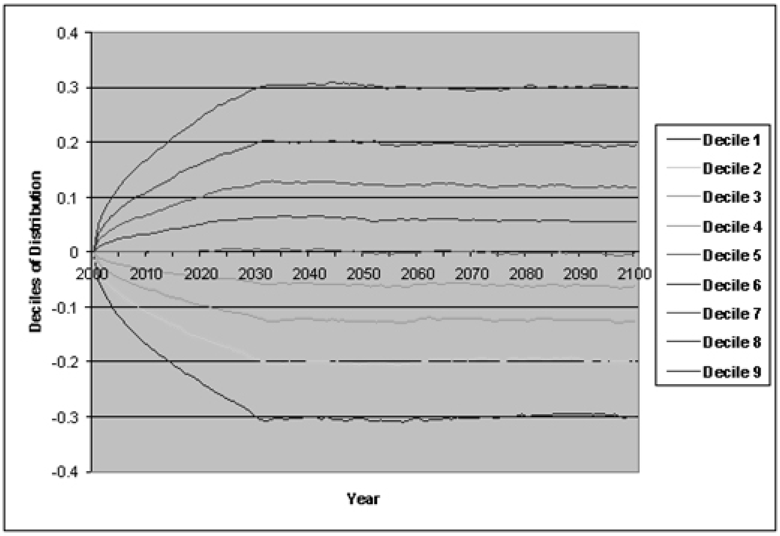

Figure 2. MA(*30*) (31 terms), $\sigma(\varepsilon_t)$=0.234, 31 initial values of *u*=0, 10,000 simulations.

fertility levels and between the deviations in changes in life expectancies across regions. In the terminology of that paper, we considered correlations between fertility and mortality deviations of 0.0 and 1.0. In the terminology of the current paper, where we consider correlations between total fertility rates deviations and life expectancy change deviations, the correlations are 0.0 and -1.0. Compared to a correlation of 0.0, the correlation of -1.0 between fertility and life expectancy change deviations produced relatively small decreases in the means of the world population size distributions and relatively large decreases in the standard deviations. This is because high fertility combined with low life expectancies partially offset each other in terms of population size.

It is difficult to do an empirical analysis of past correlations between fertility and life expectancy deviations for our 13 regions. We did an approximate calculation using United Nations data by taking, where possible, a large country in each of our regions. We took United Nations vital rate assumptions from the 1988 assessment (United Nations 1989) and used them as the trend and calculated deviations from the trend for 1995-2000 using data from the 2000 assessment (United Nations 2001). The thirteen countries are Egypt, Nigeria, China, Indonesia, Japan, Pakistan, Iran, India, Poland, France, Brazil, United States, and Bulgaria. The correlation between deviations in the total fertility rate and life expectancy at birth was 0.259, which is not statistically significantly different from zero (95 percent level of confidence, two-tailed test). On theoretical grounds there is no clear expectation as to what correlation should be expected in the future. That is why we chose 0.0, but also performed sensitivity analyses to see how our results would be affected by possible deviations from this assumption.

The sensitivity analysis presented here is at the level of one region, North Africa. This region was chosen because the quality of the demographic data in the region is quite good and because its population has a relatively low probability of reaching a peak within the century. The relatively low probability provides room for both upward and downward movements. If we were to present the results at the world level, we would have somewhat different results depending on the interregional correlations that we chose. Considering a single region allows us to present the effects more clearly. To further simplify matters, we have used only the female population. This, in no way, affects the generality of our findings.

Our results are presented in Table 1 and Figure 3. Table 1 shows the same phenomenon that we observed in our earlier work. The main effect of changing the correlation between fertility and life expectancy is on the variance of the distribution of future population sizes. For example, in 2100 when the correlation is -0.9 the 80 percent prediction interval is 123.6 million people wide, while when it is 0.9 it is 172.9 million people wide.

Figure 3 shows the probability of the female population reaching a peak for each year of the century for five different correlations between fertility and life expectancy, -0.9, -0.5, 0.0, 0.5, and 0.9 and for the 31 term moving average specification. By the end of the century, the five lines are so close to one another that they are barely distinguishable. In 2100, when the correlation is 0.0, the probability of the peak population being reached by the end of the century is 75.9 percent. If the correlation was 0.5, the probability would be 76.2 percent and if it was -0.5, it would be 74.5 percent. Therefore, if the correlation was somewhere between -0.5 and 0.5 and we supposed it to be 0.0, the maximum error in the probability of the peak being reached by the end of the century would be 1.4 percentage points. Indeed, if the true correlation was somewhere between -0.9 and 0.9 and we assumed it to be equal to zero, the maximum possible error that we could make in the probability of the peak being reached by the end of the century would be 3 percentage points. The results are similar for all regions.

The dataset with 1,000 simulations for the female population of North Africa for the case of the correlation -0.9 is in the file "nature_dataset_1a.xls." A similar dataset based on the assumption of a correlation of 0.9 is in "nature_dataset_1b.xls."

2.b Autocorrelation

For clarity, we also consider differences in first-order autocorrelation only for females in North Africa. Figure 4 is similar to Figure 3 except that it assumes zero correlation between

Table 1. Median and 80 percent prediction interval (in parentheses) for the female population of North Africa, 31-term moving average specification, correlations of deviations from average paths of the total fertility rate and changes in female life expectancy at birth of -0.9, 0.0, and 0.9.

Fertility – Life Expectancy Deviation Correlation	**2000**	**2025**	**2050**	**2075**	**2100**
-0.9	85.8	129.5 (116.3-141.7)	160.9 (133.1-187.9)	178.6 (132.7-224.3)	174.3 (119.3-242.9)
0.0	85.8	129.0 (114.6-144.2)	161.1 (127.7-196.5)	177.3 (122.9-235.4)	176.3 (107.8-260.5)
0.9	85.8	129.8 (113.2-145.4)	160.1 (126.2-202.1)	174.4 (117.6-247.0)	175.0 (100.9-273.8)

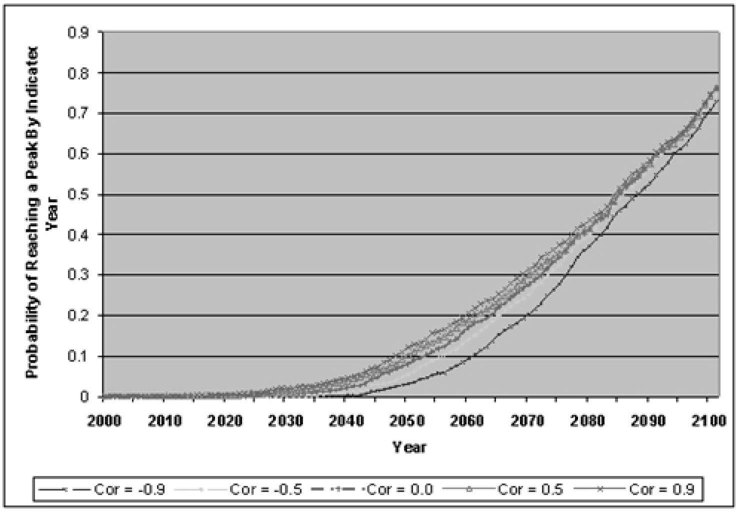

Figure 3. Probability of the female population of North Africa reaching a peak by indicated year using 31-term moving average specification for correlations between total fertility rate of female life expectancy at birth of -0.9, -0.5, 0.0, 0.5, and 0.9.

fertility and life expectancy change deviations and considers three different numbers of terms in the moving average specification, 21, 31, and 41. The three lines are quite close to one another. The probabilities of reaching a peak by the end of the century are 78.9, 75.9, and 73.3 percent, respectively. In the text, our findings are based on a moving average specification with 31 terms. If the correct specification were somewhere between 21 and 41 terms, the maximum error that we would make in the probability of a peak being reached by the end of the century would be 3 percentage points upwards or 2.6 percentage points downward. A similar clustering occurs when this sensitivity analysis is carried out assuming the other four correlations between fertility and life expectancy change deviations discussed in the previous section. The autocorrelation coefficient for our 31-term case is 0.9677.

There are not enough time periods to make a useful empirical analysis of autocorrelation even from United Nations data. Our choice is consistent with Lee (1999, p.161), which reports that the first-order correlation for the total fertility rate during the twentieth century in the United States was 0.96. Further, 31 years is close to the length of a generation and one way of interpreting Lee's finding is that there were influences on fertility that operated on generational scale.

2.c Correlations Across Regions

Due to rapidly increasing globalisation of medical technology as well as of new threats to life, it is assumed that the interregional correlations of the deviations from the expected trends in life expectancy improvements are very high. For fertility increasing globalisation of media (transmission of norms and fashions with respect to fertility relevant life styles) as well as reproductive technology is also likely to result in high global correlations. But due to the fact that fertility is much more strongly embedded in regional norms, traditions and religions the correlation is assumed to be somewhat lower than in the case of life expectancy.

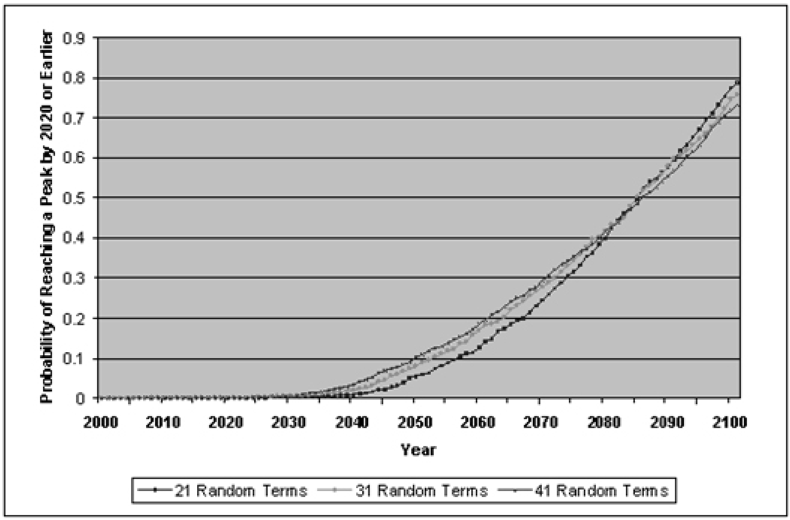

Figure 4. Probability of the female population of North Africa reaching a peak by indicated year using correlation of 0.0 between total fertility rate and female life expectancy at birth for moving average specifications of 21, 31, and 41 terms.

For the results presented in the main text interregional correlations in the deviations from expected trends were assumed to be 0.9 in the case of life expectancy and 0.7 in the case of fertility. Under these assumptions, the probability that world population growth would come to an end during this century is 86 percent. We did two other computations, one in which the interregional correlation for life expectancy was lowered to 0.7 and the one for fertility was decreased to 0.5, and another with correlations 0.7 and 0.0, respectively. The probability that the world's population growth would end by 2100 remains virtually constant in all three cases with differences only visible around the middle of the century (see Figure 5).

Table 2 gives the median world population size and the 80 percent prediction intervals for the years 2000, 2025, 2050, 2075, and 2100. The table shows that median world population sizes are hardly affected by changing the correlation structure, but that the 80 percent prediction interval is. For example, in 2100 the 80 percent prediction interval for the interregional fertility correlation of 0.7 and the interregional life expectancy correlation of 0.9 is 6.54 billion people. In the case of fertility correlation of 0.0 and life expectancy correlation of 0.7, the 80 percent prediction interval is only 4.03 billion people wide. But as shown above, this does not significantly affect the probability of world population peaking by the end of this century.

The dataset incorporating 2,000 simulations at intervals of five years for our base case with interregional fertility correlation of 0.7 and interregional life expectancy correlation of 0.9 appears in file "nature_dataset_2.xls."

3. Baseline Errors

Errors in the baseline data of a population projection are a significant source of error of the projected population especially in the nearer term future. In the longer run errors in the assumed trends dominate. The analysis of these issues in the U.S. National Research

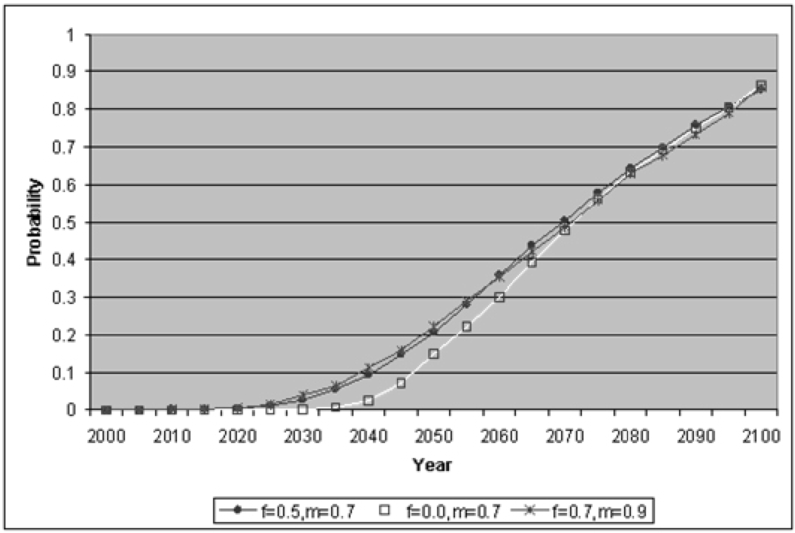

Figure 5. Probability that the peak in population size is reached before the indicated date for three different structures of interregional correlations. f=interregional correlation in total fertility rates; m=interregional correlation in life expectancies at birth.

Table 2. Median world population size and 80 percent prediction intervals (in parentheses) for three sets of interregional correlations of deviations from average paths of total fertility rates and changes in life expectancies at birth.

	2000	2025	2050	2075	2100
Fertility Corr. = 0.7, Life Exp. Corr. = 0.9	6.06	7.83 (7.22-8.46)	8.80 (7.35-10.44)	8.95 (6.64-11.65)	8.41 (5.58-12.12)
Fertility Corr. = 0.5, Life Exp. Corr. = 0.7	6.06	7.80 (7.23-8.38)	8.78 (7.41-10.20)	8.83 (6.78-11.22)	8.35 (5.73-11.42)
Fertility Corr. = 0.0, Life Exp. Corr. = 0.7	6.06	7.80 (7.46-8.16)	8.78 (7.97-9.71)	8.89 (7.45-10.49)	8.43 (6.51-10.54)

Council (NRC) report (2000), which was based on earlier important work by Alho (1992) and Keilman (1999), has recently been further developed by Bulatao (2001) who distinguishes between the errors in the baseline population size, the errors in the assumed starting levels in fertility and mortality and the errors due to wrong assumption on the trends. His decomposition of the errors for selected UN and World Bank forecasts since 1973 attributes a smaller proportion of the total error to baseline errors than the NRC report did. Studying the errors at different levels of regional aggregation he concludes that world errors tend to be much smaller than the error for the average country because country errors have tended to offset.

What do these findings from past projections imply for the uncertainty ranges of future population trends presented here? In the following we will discuss (a) the sensitivity of assumed serious errors in the baseline population on our main results and (b) how assumed changes in the starting level of fertility (using the recently announced UN projections United Nations 2001 as an example) impact our main conclusion.

3a. Errors in Baseline Population Size

We did calculations assuming that the true population of sub-Saharan Africa in 2000 was 5 percent and 10 percent higher than our figure. These are very high baseline errors for a world region by any standards. The consequence of this was that the probability of the world's population reaching a peak by 2100 was reduced by one-tenth of one percentage point (for both the 5 and 10 percent changes). The mean of the world's population distribution would be around 173 million people or roughly 2 percent higher in 2100 than we forecast, if the true population of sub-Saharan Africa in 2000 were 10 percent higher than our figure. The effect of an error in initial population size will be larger in sub-Saharan Africa than in other regions because of the still rapid population growth there. In the opposite case of overestimating the population of Sub-Saharan Africa in 2000, the probability of world population growth ending during this century would be slightly higher than our figure. This sensitivity analysis shows that plausible errors in initial population sizes will have virtually no impact on our conclusion that the world population growth is likely to end in the current century.

3b. Errors in Baseline Total Fertility Rates

By using the recently released UN (2001) population forecasts we can assess the effects of plausible changes in baseline total fertility estimates. Between 1999 and 2001 the UN has reassessed its estimates of fertility levels for 1995-2000 and increased fertility figures for some large countries in sub-Saharan Africa and South Asia. This change in baseline fertility is one of the sources (along with changed assumptions about trends) of an increase in projected world population sizes from UN (1999) to UN (2001).

Here we study the sensitivity of our findings to the changed UN baseline fertility assumptions. Our results are presented in Tables 3 and 4, where we utilise all the assumptions in our paper, except that we adjust our total fertility rates in the initial year according to the differences in estimates of 1995-2000 fertility between UN (1999) and UN (2001). In Table 3, we show the probability of a peak in population size being reached for the world and for our 13 regions for 25-year intervals from 2000 to 2100 using both total fertility rate sets as starting values. Using the higher total fertility rates, the probability that the world's population would peak during the century is 85.7 percent, compared to 86.0 percent using our original total fertility rates. The effect of this plausible increase in baseline total fertility rates has a negligible effect on the probability of reaching a peak in all regions of the world as shown in Table 3.

Table 4 shows the median population size and 80 percent prediction interval for the world's population and the population of our 13 regions by 25-year intervals from 2000 to 2100. It is the analogue of Table 1 in the main text but based on higher initial total fertility rates. Using the lower total fertility rates, the world's median population size in 2100 is 8.41 billion with an 80 percent prediction interval between 5.58 and 12.12 billion people. With the higher total fertility rates, the world's median population size in 2100 is 8.45 billion with an 80 percent prediction interval between 5.57 and 12.22 billion. It is clear that adjusting the baseline total fertility rates higher has little effect on the distribution of future world population sizes in 2100

Table 3. Probability that population will reach a peak before the given date using total fertility rates based on the assumptions used in the text and those with higher baseline fertility following the UN[3] (2001) assessment.

Region	**2075**		**2100**	
	TFR Used in paper	TFR Higher baseline fertility	TFR Used in paper	TFR Higher baseline fertility
World	0.557	0.557	0.860	0.857
European Former Soviet Union	0.935	0.949	0.973	0.979
Eastern Europe	0.928	0.933	0.972	0.972
Western Europe	0.782	0.777	0.939	0.935
Pacific OECD	0.839	0.837	0.959	0.957
Pacific Asia	0.592	0.588	0.869	0.866
China Region	0.814	0.810	0.937	0.932
South Asia	0.681	0.680	0.924	0.923
Middle East	0.313	0.323	0.715	0.712
Central Asia	0.379	0.382	0.754	0.751
Latin America	0.324	0.324	0.666	0.659
North America	0.367	0.373	0.703	0.699
Sub-Saharan Africa	0.337	0.339	0.734	0.729
North Africa	0.363	0.385	0.753	0.750

Conclusion

The main finding of our paper is that there is a high probability, around 85 percent, that the population of the world will reach a peak sometime during the current century. We have considered the sensitivity of this finding to a number of uncertain parameters. The evidence strongly supports the conclusion that our main finding is not sensitive to plausible changes in those parameters.

Table 4. Median population sizes and 80 percent prediction intervals (in parentheses) using all the same assumptions as Table 1 in the main text but with total fertility adjusted upwards according to the differences between UN (1999) and UN (2001).

Region	**2000**	**2025**	**2050**	**2075**	**2100**
World [billions]	6.06	7.86 (7.23-8.50)	8.84 (7.36-10.50)	9.00 (6.65-11.71)	8.45 (5.57-12.22)
European Former Soviet Union [millions]	235.64	215.45 (199.26-231.07)	182.28 (148.57-219.53)	152.35 (104.33-209.96)	134.13 (79.63-209.97)
Eastern Europe [millions]	121.19	116.54 (108.12-124.58)	102.56 (84.54-123.01)	85.24 (59.17-117.17)	72.94 (42.54-113.65)
Western Europe [millions]	455.63	477.86 445.30-509.51)	470.37 (398.55-551.28)	434.10 (321.26-563.53)	391.10 (255.75-569.63)
Pacific OECD [millions]	149.93	154.70 (143.61-165.58)	148.40 (124.42-174.50)	135.38 (99.70-175.83)	122.45 (78.54-172.50)
Pacific Asia [millions]	476.43	626.34 (568.23-683.40)	701.60 (573.37-844.29)	702.05 (507.59-938.20)	652.33 (407.92-947.95)
China Region [billions]	1.41	1.61 (1.49-1.72)	1.58 (1.30-1.86)	1.42 (1.00-1.89)	1.25 (0.76-1.88)
South Asia [billions]	1.37	1.95 (1.74-2.16)	2.26 (1.80-2.79)	2.25 (1.54-3.10)	1.97 (1.19-3.04)
Middle East [millions]	172.12	284.60 (251.38-317.63)	367.39 (299.58-443.60)	411.97 (294.99-541.89)	410.02 (258.15-592.87)
Central Asia [millions]	55.88	81.28 (72.65-90.01)	99.64 (79.31-120.96)	106.82 (75.20-144.89)	105.42 (65.73-159.17)
Latin America [millions]	515.27	708.86 (641.17-776.57)	840.11 (677.68-1006.83)	904.47 (644.97-1202.10)	933.11 (583.87-1385.09)
North America [millions]	313.67	379.54 (350.77-410.72)	422.46 (357.84-498.40)	440.46 (342.93-566.49)	452.61 (311.39-630.19)
Sub-Saharan Africa [millions]	611.19	1000.76 (874.92-1126.09)	1358.10 (1039.89-1747.53)	1569.20 (1058.01-2253.84)	1542.84 (901.33-2515.01)
North Africa [millions]	173.26	253.49 (224.62-281.40)	305.07 (243.26-372.08)	327.05 (231.14-434.54)	323.90 (207.67-471.19)

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The Coming Acceleration of Global Population Ageing[1]

Wolfgang Lutz, Warren C. Sanderson and Sergei Scherbov

The future paths of population ageing result from specific combinations of declining fertility and increasing life expectancies in different parts of the world (United Nations 2007). Here we measure the speed of population ageing by using conventional measures and new ones that take changes in longevity into account for the world as a whole and for 13 major regions. We report on future levels of indicators of ageing and the speed at which they change. We show how these depend on whether changes in life expectancy are taken into account. We also show that the speed of ageing is likely to increase over the coming decades and to decelerate in most regions by mid-century. All our measures indicate a continuous ageing of the world's population throughout the century. The median age of the world's population increases from 26.6 years in 2000 to 37.3 years in 2050 and then to 45.6 years in 2100, when it is not adjusted for longevity increase. When increases in life expectancy are taken into account (Sanderson & Scherbov 2005; Sanderson & Scherbov 2007), the adjusted median age rises from 26.6 in 2000 to 31.1 in 2050 and only to 32.9 in 2100, slightly less than what it was in the China region in 2005. There are large differences in the regional patterns of ageing. In North America, the median age adjusted for life expectancy change falls throughout almost the entire century, whereas the conventional median age increases significantly. Our assessment of trends in ageing is based on new probabilistic population forecasts. The probability that growth in the world's population will end during this century is 88%, somewhat higher than previously assessed (Lutz et al. 2001). After mid-century, lower rates of population growth are likely to coincide with slower rates of ageing.

Conventional measures of ageing are based on chronological age. They assume that a 60-year-old person in 1900 was just as old as a 60-year-old person in 2000 because each has lived the same number of years. However, would we say that the two have aged at the same rate?

After all, the 60-year-old in 2000 would, on average, have many more remaining years of life. Population ageing is not only about there being more old people (by today's definition of what is old): it is also about people living longer lives (Harper 2006). To capture this important impact of increasing life expectancy on our lives, and on the definitions of what is age and what is old, we introduce and quantify three new indicators of age that explicitly take changes in the remaining life expectancy into account. Although traditional age still greatly matters for institutional arrangements such as pension systems in most countries, the alternative measures tell us more about the changing human condition in which more people can plan for a longer and healthier life with consequences for their behavior.

The conventional measures considered here are the proportion of the population aged 60+ (Prop. 60+), the median age of the population (MA) and its average age (Aver. Age). The alternative approach to measuring the proportion of elderly people in the population does not depend on a fixed age boundary but, rather, on a fixed remaining life expectancy. We define Prop. RLE 15– as the proportion of the population in age groups that have a remaining life expectancy of 15 years or less (see Ryder 1975 for the suggestion of a similar measure). If longevity increases, the minimum age of people included in Prop. RLE 15–

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increases. The adjusted version of the median age is called standardized or prospective median age (PMA) (Sanderson & Scherbov 2005; Sanderson & Scherbov 2007). It is the age of a person in the year 2000 who has the same remaining life expectancy as a person at the median age in the year under consideration. The change in the prospective median age over some time period is roughly the change in the median age minus the change in life expectancy at the median age.

The adjusted version of the average age is the population average remaining years of life (PARYL). It is the weighted average of age-specific remaining life expectancies, where the weights are the proportions of the population at each age (Hersch 1944; Panush & Peritz 1996). PARYL gives us the average remaining years of life of population members. Unlike the other measures, PARYL goes down as a population ages. We intuitively think of populations being younger when, on average, its members have more years left to live and PARYL is higher.

Figure 1 shows four of these measures of ageing as they evolve over time for the global population. All six measures are listed in Table 1 for selected regions and dates (information for all regions is given in Supplementary Table 2). All of them indicate that ageing will continue throughout the century. The two most rapidly increasing indicators, the proportion of the population 60+ years old and the median age of the population, are based on the traditional definition of age, hence suggesting the need for institutional adjustments to cope with these expected increases. The proportion of the global population 60+ years old increases from 10.0% in 2000 to 21.8% in 2050 and then to 32.2% in 2100. The three measures that are adjusted for longevity change show a slower pace of change.

Prop. RLE 15- goes from 7.4% in 2000 to 12.0% in 2050, and then to 15.6% in 2100. As to regional differentials, Table 1 shows that Japan/Oceania is the oldest region today and is likely to keep this position throughout the century with its median age likely to increase to above 60 years. It is closely followed by the European regions. North America shows much slower ageing and is likely to be surpassed by China for every indicator of ageing by 2030-40.

Figure 2 shows the accelerating and then decelerating speed of ageing at the global level. It plots decadal changes in the level of the indicator divided by the maximum increase

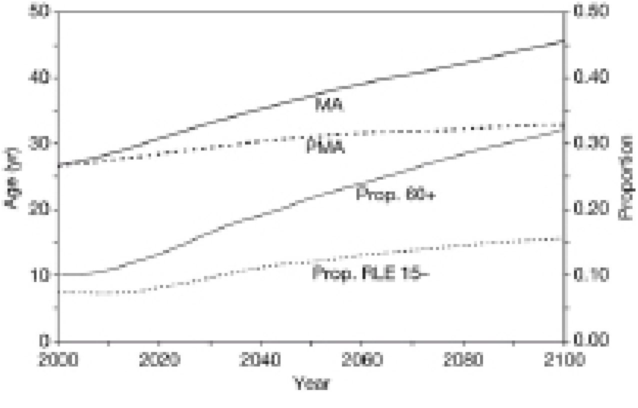

Figure 1. Projected changes in the level of ageing for the world population over the course of the century for four indicators of ageing as defined in the text.

Table 1. Indicators of ageing

Region	Indicator	2000	2005	2010	2020	2030	2040	2050	2075	2100
North America	Aver. Age	36.5	37.0	37.7	39.5	41.3	42.6	43.6	46.5	49.5
	Prop. 60+	0.16	0.17	0.18	0.23	0.27	0.28	0.30	0.35	0.39
	PARYL	43.0	43.3	43.4	43.5	43.6	44.1	45.0	46.3	48.4
	MA	35.9	36.7	37.2	38.4	40.3	41.9	43.0	47.0	50.0
	Prop. RLE 15-	0.11	0.10	0.10	0.11	0.13	0.15	0.14	0.15	0.15
	PMA	35.9	35.8	35.4	34.7	34.8	34.6	33.7	33.0	30.9
Middle East	Aver. Age	24.2	25.1	26.0	28.3	31.4	34.4	37.1	42.6	46.6
	Prop. 60+	0.06	0.06	0.06	0.08	0.10	0.14	0.19	0.28	0.34
	PARYL	48.8	48.8	48.7	48.3	47.0	45.8	44.9	43.5	43.7
	MA	19.9	21.2	22.6	25.5	28.7	32.3	35.9	42.4	47.4
	Prop. RLE 15-	0.04	0.04	0.04	0.05	0.06	0.07	0.09	0.13	0.16
	PMA	19.9	20.3	20.9	22.0	23.5	25.5	27.6	30.0	30.6
South Asia	Aver. Age	26.5	27.1	27.8	29.8	32.2	34.6	37.0	42.4	47.3
	Prop. 60+	0.07	0.07	0.08	0.09	0.12	0.14	0.17	0.26	0.35
	PARYL	44.1	44.1	43.9	43.2	42.1	41.2	40.4	38.6	37.6
	MA	22.7	23.4	24.5	26.9	29.6	32.8	35.9	42.6	48.5
	Prop. RLE 15-	0.06	0.06	0.06	0.07	0.08	0.10	0.11	0.16	0.19
	PMA	22.7	22.9	23.4	24.7	26.3	28.3	30.2	33.7	36.2
China region	Aver. Age	31.2	33.2	35.1	38.6	42.3	45.5	47.7	50.7	51.2
	Prop. 60+	0.10	0.11	0.12	0.17	0.24	0.30	0.35	0.41	0.42
	PARYL	43.4	42.1	41.0	39.0	36.9	35.5	35.0	36.1	39.3
	MA	29.6	32.3	34.7	38.5	43.0	47.5	50.7	53.7	54.0
	Prop. RLE 15-	0.07	0.08	0.08	0.11	0.14	0.19	0.21	0.24	0.22
	PMA	29.6	31.7	33.5	36.0	39.3	42.3	44.1	43.0	38.6
Pacific Asia	Aver. Age	28.2	29.3	30.5	33.0	35.4	37.6	39.5	43.2	47.5
	Prop. 60+	0.08	0.08	0.09	0.12	0.16	0.20	0.23	0.29	0.36
	PARYL	44.7	44.4	43.9	42.9	42.1	41.5	41.2	41.2	41.1
	MA	25.3	26.9	28.4	31.4	34.0	36.4	38.6	43.3	48.7
	Prop. RLE 15-	0.06	0.06	0.07	0.08	0.10	0.12	0.14	0.15	0.17
	PMA	25.3	26.2	27.1	28.7	29.9	30.9	31.6	32.4	33.7
Japan/Oceania	Aver. Age	40.4	41.6	43.0	45.7	47.9	49.7	51.3	54.1	57.7
	Prop. 60+	0.22	0.24	0.27	0.31	0.35	0.40	0.42	0.47	0.51
	PARYL	41.3	41.0	40.6	39.7	39.5	39.5	39.6	41.1	43.0
	MA	40.0	41.3	42.8	46.7	49.9	52.1	53.9	57.6	61.1
	Prop. RLE 15-	0.13	0.13	0.14	0.17	0.18	0.18	0.20	0.21	0.21
	PMA	40.0	40.3	40.9	42.9	44.3	44.6	44.5	43.3	41.7
Western Europe	Aver. Age	38.3	39.1	40.1	42.4	44.7	46.8	48.4	51.0	53.5
	Prop. 60+	0.20	0.20	0.21	0.25	0.31	0.34	0.37	0.42	0.46
	PARYL	41.0	41.0	40.8	40.3	39.8	39.6	39.7	41.4	43.5
	MA	36.8	38.3	40.0	43.1	45.8	48.2	50.2	53.5	56.5
	Prop. RLE 15-	0.13	0.13	0.13	0.14	0.15	0.18	0.19	0.20	0.19
	PMA	36.8	37.5	38.3	39.6	40.5	41.1	41.3	39.8	37.7
Eastern Europe	Aver. Age	37.0	38.4	39.8	42.7	45.6	48.2	50.3	52.4	52.4
	Prop. 60+	0.18	0.18	0.20	0.25	0.29	0.36	0.42	0.44	0.44
	PARYL	39.7	39.1	38.5	37.3	36.0	35.3	34.9	36.9	40.6
	MA	35.6	37.1	38.9	42.9	47.3	51.3	54.0	55.7	55.7
	Prop. RLE 15-	0.13	0.13	0.13	0.15	0.18	0.19	0.22	0.24	0.21
	PMA	35.6	36.4	37.4	39.9	42.8	45.2	46.3	43.5	38.6
World	Aver. Age	29.7	30.4	31.3	33.1	35.2	37.1	38.8	42.3	45.5
	Prop. 60+	0.10	0.10	0.11	0.13	0.17	0.19	0.22	0.27	0.32
	PARYL	43.8	43.6	43.3	42.8	42.1	41.6	41.3	41.0	41.2
	MA	26.6	27.5	28.4	30.8	33.2	35.3	37.3	41.4	45.6
	Prop. RLE 15-	0.07	0.07	0.07	0.08	0.10	0.11	0.12	0.14	0.16
	PMA	26.6	27.0	27.5	28.5	29.4	30.4	31.1	32.1	32.9

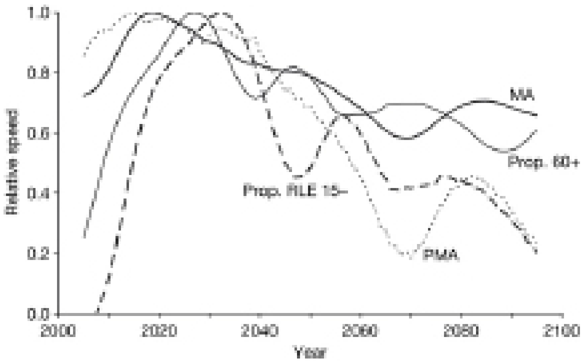

Figure 2. The changing speed of increase in selected indicators of ageing. This is calculated as increases per decade in the level of the indicator divided by the maximum increase projected over the century; on the time axis, values are allocated to the middle of the decade considered.

(speed) projected over the century. For all indicators, the speed accelerates over the coming years reaching the highest rate of increase before 2035. After that, the speed of ageing is expected to decelerate although there will be further increases in the level of ageing throughout the century. This analysis clearly shows that, even under widely differing definitions of ageing, the world is expected to experience a significant acceleration in the speed of population ageing over the coming years.

How certain are these projected future trends in ageing? Is the expected rapid increase in ageing in many parts of the world a near certainty or just one out of several possible scenarios? The probabilistic nature of our population projections explicitly addresses this issue. Figure 3 shows the cumulative probabilities that different world regions reach one-third of their population 60+ years old (Prop. 60+) over the course of the century. By mid-century, the chance of having passed this specific ageing threshold is 98% in Japan/Oceania, 82% in Western Europe and even 69% in the China region. Uncertainty is so low in these regions because past fertility and mortality declines have already altered the age structures

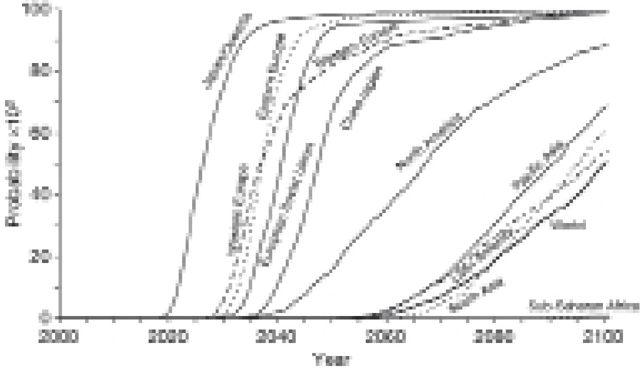

Figure 3. Cumulative probabilities of reaching a proportion 60+ of one-third or more for the world and selected world regions by calendar year.

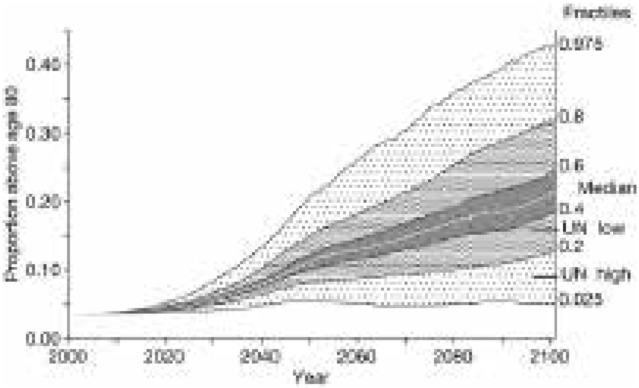

Figure 4. Fractiles of the projected uncertainty distribution of the proportion of the population above age 80 in Western Europe. Straight lines in 2100 indicate the values given by the high and low variants of the United Nations (UN) long-term population projections.

significantly. North America has a 50% chance of crossing this threshold in the 2060s owing to its currently still younger age structure and anticipated future migration gains. For sub-Saharan Africa, which still has an extremely young population with 44% of the population below age 15, the chance of Prop. 60+ being more than a third of the population is close to zero, even by the end of the century. For all other regions the chances start to increase over the 2060s and 2070s and reach around 50% by the end of the century. For the world as a whole, the cumulative probability turns out to be exactly 50% in 2100.

Figure 4 demonstrates another advantage of studying ageing from a probabilistic viewpoint. It shows predicted distributions of the proportion above age 80 for Western Europe (see Supplementary Table 1 for data on all regions). The proportion 80+ is almost certain to increase significantly over the coming decades. The projected increase in this indicator is very sensitive to the assumptions about future trends in old-age mortality where our assumed uncertainty ranges reflect tremendous disagreement among scientists (National Research Council 2000; Bongaarts 2006; Fries 1980; Keilman 1997; Lee & Carter 1992; Manton et al. 1991; Oeppen & Vaupel 2002; Carnes & Olshansky 2007). Figure 4 shows that the 95% prediction interval is 5.5-20.7% by 2050 and 5.0-42.8% by 2100. The small lines inserted in 2100 give the results from the high and low variants of the most recent United Nations long-range projections (United Nations 2004). These only reflect alternative fertility levels because the United Nations does not publish variants considering mortality uncertainty. That approach leads to a gross underestimation of the uncertainty of the future proportions of elderly.

Population ageing has many dimensions that will affect individuals and societies alike. When we supplement the conventional measures of ageing with ones that incorporate longevity change, we obtain a more complete understanding of how these dimensions are expected to evolve. In addition to changes in its level, the speed of ageing matters because, generally, the difficulties of adaptation to demographic change increase with the speed of change. In this respect, the world as a whole and the low fertility countries in particular face the challenge of an accelerating speed of ageing over the coming decades with the prospect of a slower speed of ageing at a higher level towards the second half of the century.

Methods summary

The population forecasts presented here are an update of earlier probabilistic forecasts published in 2001 (Lutz et al. 2001). A fuller list of the results of this update is given in Supplementary Table 1. Although the methodology and the longer-term assumptions have not changed, the new forecasts reflect empirical trends and new data available up to 2006. One methodological innovation lies in the consideration of uncertainty ranges for starting conditions in certain regions of the world with unreliable information. This was particularly relevant for the assumed level of current fertility in China, where published total fertility rates range from 1.2 to 1.8. After a review of 18 different estimates (Lutz et al. 2007), we assumed a median total fertility rate of 1.5 and an 80% uncertainty range from 1.3 to 1.7 as starting conditions. This change causes a downward shift in the projected long- term global population size, which is offset by the effects of the observed slower decline of fertility in sub-Saharan Africa, leaving forecasted world population sizes largely unaffected. Sensitivity analyses showed that the main findings about the coming acceleration of global ageing hold, even if China is excluded from the simulations. The proportion of our simulations that show a peak in the world's population some time during the century increases from 86% in our previous forecasts to 88% in our current ones (see Supplementary Figure 1). The forecasting methodology is described in ref. 4 and all the long-term assumptions are described and justified in detail in Lutz et al. (2004). New short- and medium-term fertility assumptions are given in Supplementary Table 3. The mortality and migration assumptions were unchanged. The list of countries in each region appears in Lutz et al. (2004).

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Supplementary Information for "The Coming Acceleration of Global Population Ageing"[1]

Wolfgang Lutz, Warren C. Sanderson and Sergei Scherbov

Supplementary Table 1: Results of the 2007 probabilistic population forecast.

Upper figures in each cell are median values of 1000 simulations. Figures in parentheses show 80 percent prediction intervals. (Figures for total population are in millions except for the World, the China region and South Asia, where it is in billions.)

Region	Indicator	2000	2005	2010	2020	2030	2040	2050	2075	2100
North Africa	*Aver. Age*	25.5	26.4	27.3 (27.1-27.6)	29.7 (28.6-30.8)	32.5 (31.2-34.0)	35.2 (33.4-37.0)	37.5 (35.2-39.8)	41.7 (38.8-45.7)	44.6 (40.3-51.0)
	Prop. 60+	0.06	0.06	0.07 (0.07-0.07)	0.09 (0.09-0.09)	0.12 (0.11-0.13)	0.15 (0.13-0.17)	0.19 (0.16-0.22)	0.27 (0.22-0.34)	0.31 (0.24-0.42)
	Prop. 80+	0.005	0.005	0.006 (0.006-0.006)	0.008 (0.007-0.008)	0.010 (0.009-0.012)	0.017 (0.014-0.023)	0.024 (0.018-0.036)	0.053 (0.030-0.102)	0.090 (0.043-0.195)
	Total Population	173.3	190.2	207.6 (205.3-210.1)	239.8 (228.2-250.8)	265.6 (247.4-283.8)	287.0 (260.1-316.4)	304.6 (267.3-346.2)	326.6 (261.1-399.7)	322.7 (236.4-432.9)
Sub Saharan Africa	*Aver. Age*	22.1	21.6 (21.5-21.8)	21.6 (21.2-22.0)	22.2 (21.4-23.2)	23.7 (22.5-25.0)	25.4 (23.8-27.2)	27.3 (25.5-29.7)	32.9 (30.6-35.7)	38.0 (35.4-41.7)
	Prop. 60+	0.05	0.04 (0.04-0.04)	0.04 (0.04-0.04)	0.05 (0.04-0.05)	0.05 (0.05-0.05)	0.05 (0.05-0.06)	0.07 (0.06-0.08)	0.13 (0.11-0.17)	0.20 (0.16-0.25)
	Prop. 80+	0.003	0.003 (0.003-0.003)	0.003 (0.003-0.003)	0.003 (0.003-0.003)	0.003 (0.003-0.003)	0.004 (0.003-0.004)	0.005 (0.004-0.006)	0.010 (0.007-0.015)	0.024 (0.015-0.054)
	Total Population	611.2	704.6 (698.3-710.6)	799.7 (781.3-815.5)	989.2 (924.9-1044.6)	1186.1 (1069.1-1297.5)	1394.0 (1216.2-1587.6)	1597.4 (1337.2-1892.7)	1989.6 (1485.5-2531.3)	2068.4 (1386.1-2874.3)
North America	*Aver. Age*	36.5	37.0	37.7 (37.4-38.1)	39.5 (38.4-40.5)	41.3 (39.5-43.0)	42.6 (40.0-45.1)	43.6 (40.1-47.0)	46.5 (41.4-51.6)	49.5 (42.2-57.1)
	Prop. 60+	0.16	0.17	0.18 (0.18-0.18)	0.23 (0.22-0.24)	0.27 (0.24-0.29)	0.28 (0.24-0.32)	0.30 (0.24-0.35)	0.35 (0.26-0.42)	0.39 (0.28-0.49)
	Prop. 80+	0.032	0.030	0.030 (0.029-0.030)	0.031 (0.028-0.035)	0.048 (0.038-0.061)	0.073 (0.052-0.105)	0.087 (0.051-0.136)	0.125 (0.057-0.205)	0.180 (0.068-0.294)
	Total Population	313.7	325.3	338.4 (332.0-345.0)	366.3 (350.5-383.5)	391.9 (365.5-419.2)	412.5 (370.4-453.8)	425.3 (372.8-484.0)	446.7 (362.2-538.5)	460.3 (336.8-598.5)
Latin America	*Aver. Age*	27.8	28.8	29.8 (29.6-30.0)	32.2 (31.3-33.2)	34.7 (33.3-36.2)	37.0 (35.1-39.0)	38.9 (36.4-41.9)	42.3 (38.5-46.8)	44.7 (39.6-51.7)
	Prop. 60+	0.08	0.08	0.09 (0.09-0.09)	0.11 (0.11-0.12)	0.15 (0.14-0.16)	0.19 (0.17-0.21)	0.22 (0.19-0.26)	0.28 (0.22-0.35)	0.32 (0.23-0.42)
	Prop. 80+	0.009	0.009	0.010 (0.009-0.010)	0.011 (0.011-0.012)	0.016 (0.013-0.019)	0.025 (0.019-0.035)	0.037 (0.025-0.060)	0.069 (0.035-0.132)	0.104 (0.043-0.214)
	Total Population	515.3	555.8	595.3 (589.9-600.8)	669.3 (644.3-694.9)	732.6 (691.8-779.1)	786.6 (721.5-860.4)	830.9 (734.3-933.2)	893.9 (719.7-1094.9)	935.5 (672.7-1228.5)

Uncertainty intervals in 2005 are given for the three regions in which we had uncertain initial values of the total fertility rate.

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[1] published on the website of *Nature*

Supplementary Table 1 (continued)

Central Asia	*Aver. Age*	26.9	27.8	28.7 (28.5-28.9)	30.7 (29.8-31.8)	33.4 (32.0-34.8)	35.7 (33.9-37.8)	37.9 (35.5-40.5)	42.4 (38.8-46.8)	46.0 (40.9-52.1)
	Prop. 60+	0.08	0.08	0.08 (0.08-0.08)	0.10 (0.10-0.11)	0.13 (0.12-0.14)	0.16 (0.14-0.18)	0.20 (0.17-0.24)	0.28 (0.22-0.35)	0.33 (0.25-0.43)
	Prop. 80+	0.008	0.008	0.010 (0.010-0.010)	0.012 (0.011-0.013)	0.011 (0.010-0.013)	0.021 (0.017-0.030)	0.029 (0.020-0.046)	0.064 (0.034-0.121)	0.104 (0.046-0.206)
	Total Population	55.9	60.3	65.3 (64.7-65.8)	74.9 (71.8-78.0)	82.9 (77.8-88.6)	90.1 (81.9-98.9)	95.4 (84.0-107.6)	102.6 (81.6-124.8)	100.9 (72.3-133.1)
Middle East	*Aver. Age*	24.2	25.1	26.0 (25.8-26.3)	28.3 (27.2-29.4)	31.4 (30.1-32.9)	34.4 (32.7-36.2)	37.1 (34.9-39.5)	42.6 (39.2-46.9)	46.6 (41.2-53.0)
	Prop. 60+	0.06	0.06	0.06 (0.06-0.06)	0.08 (0.07-0.08)	0.10 (0.09-0.11)	0.14 (0.12-0.16)	0.19 (0.16-0.22)	0.28 (0.22-0.35)	0.34 (0.25-0.44)
	Prop. 80+	0.005	0.005	0.006 (0.006-0.006)	0.007 (0.006-0.007)	0.009 (0.008-0.011)	0.016 (0.012-0.022)	0.024 (0.016-0.038)	0.064 (0.032-0.120)	0.112 (0.049-0.224)
	Total Population	172.1	192.4	214.4 (212.2-216.7)	257.8 (245.7-271.6)	294.3 (274.6-316.0)	327.4 (298.7-361.1)	356.7 (314.4-402.2)	391.5 (314.6-473.8)	388.5 (291.2-509.7)
South Asia	*Aver. Age*	26.5	27.1 (26.9-27.2)	27.8 (27.5-28.2)	29.8 (28.7-31.0)	32.2 (30.7-33.7)	34.6 (32.7-36.6)	37.0 (34.6-39.6)	42.4 (39.5-46.4)	47.3 (43.1-53.0)
	Prop. 60+	0.07	0.07 (0.07-0.07)	0.08 (0.07-0.08)	0.09 (0.09-0.10)	0.12 (0.11-0.13)	0.14 (0.12-0.16)	0.17 (0.15-0.21)	0.26 (0.22-0.33)	0.35 (0.27-0.44)
	Prop. 80+	0.006	0.006 (0.006-0.006)	0.007 (0.007-0.007)	0.008 (0.007-0.008)	0.010 (0.009-0.011)	0.014 (0.012-0.018)	0.020 (0.015-0.029)	0.043 (0.026-0.082)	0.083 (0.042-0.183)
	Total Population	1.4	1.5 (1.5-1.5)	1.6 (1.6-1.7)	1.9 (1.8-1.9)	2.0 (1.9-2.2)	2.2 (2.0-2.4)	2.3 (2.0-2.6)	2.3 (1.8-2.8)	2.0 (1.4-2.7)
China Region	*Aver. Age*	31.2	33.2 (33.0-33.5)	35.1 (34.7-35.6)	38.6 (37.7-39.6)	42.3 (40.8-43.9)	45.5 (43.3-47.9)	47.7 (44.7-51.3)	50.7 (45.2-56.9)	51.2 (44.6-60.3)
	Prop. 60+	0.10	0.11 (0.11-0.11)	0.12 (0.12-0.12)	0.17 (0.16-0.17)	0.24 (0.23-0.26)	0.30 (0.27-0.34)	0.35 (0.30-0.41)	0.41 (0.32-0.52)	0.42 (0.31-0.55)
	Prop. 80+	0.009	0.011 (0.011-0.011)	0.013 (0.013-0.013)	0.017 (0.016-0.019)	0.025 (0.021-0.030)	0.042 (0.033-0.058)	0.073 (0.051-0.109)	0.130 (0.069-0.237)	0.161 (0.071-0.325)
	Total Population	1.4	1.4 (1.4-1.5)	1.5 (1.4-1.5)	1.5 (1.5-1.6)	1.5 (1.4-1.6)	1.4 (1.3-1.6)	1.3 (1.2-1.5)	1.1 (0.8-1.3)	0.8 (0.6-1.2)

Supplementary Table 1 (continued)

Pacific Asia	*Aver. Age*	28.2	29.3	30.5 (30.3-30.7)	33.0 (32.1-33.9)	35.4 (34.1-36.8)	37.6 (35.8-39.6)	39.5 (37.1-42.0)	43.2 (39.8-47.7)	47.5 (42.6-54.4)
	Prop. 60+	0.08	0.08	0.09 (0.09-0.09)	0.12 (0.11-0.12)	0.16 (0.15-0.17)	0.20 (0.18-0.22)	0.23 (0.19-0.27)	0.29 (0.23-0.36)	0.36 (0.27-0.46)
	Prop. 80+	0.006	0.007	0.008 (0.008-0.008)	0.011 (0.010-0.012)	0.014 (0.013-0.017)	0.024 (0.019-0.032)	0.035 (0.026-0.054)	0.062 (0.035-0.124)	0.104 (0.046-0.220)
	Total Population	476.4	510.1	541.8 (537.3-546.0)	598.3 (577.1-619.2)	643.3 (608.0-681.9)	675.5 (621.3-739.9)	697.4 (619.5-786.7)	695.7 (562.1-841.4)	637.9 (477.8-869.4)
Japan/ Oceania	*Aver. Age*	40.4	41.6	43.0 (42.8-43.3)	45.7 (44.6-46.8)	47.9 (45.9-49.9)	49.7 (46.8-52.8)	51.3 (47.3-55.7)	54.1 (47.4-62.0)	57.7 (48.4-67.6)
	Prop. 60+	0.22	0.24	0.27 (0.27-0.28)	0.31 (0.30-0.33)	0.35 (0.32-0.38)	0.40 (0.35-0.44)	0.42 (0.36-0.49)	0.47 (0.36-0.57)	0.51 (0.37-0.62)
	Prop. 80+	0.035	0.038	0.046 (0.045-0.047)	0.064 (0.057-0.073)	0.097 (0.077-0.123)	0.114 (0.078-0.164)	0.138 (0.084-0.212)	0.202 (0.094-0.335)	0.272 (0.111-0.422)
	Total Population	149.9	151.2	151.5 (150.3-152.9)	150.3 (145.5-155.0)	147.5 (138.8-156.4)	142.3 (129.6-156.9)	135.4 (118.3-154.6)	114.4 (88.9-143.8)	98.9 (68.3-130.2)
Western Europe	*Aver. Age*	38.3	39.1	40.1 (39.9-40.3)	42.4 (41.4-43.4)	44.7 (42.8-46.4)	46.8 (44.1-49.4)	48.4 (44.7-52.4)	51.0 (44.8-57.7)	53.5 (45.9-63.2)
	Prop. 60+	0.20	0.20	0.21 (0.21-0.22)	0.25 (0.24-0.26)	0.31 (0.28-0.33)	0.34 (0.30-0.39)	0.37 (0.31-0.43)	0.42 (0.32-0.51)	0.46 (0.34-0.57)
	Prop. 80+	0.033	0.034	0.037 (0.036-0.037)	0.043 (0.039-0.049)	0.057 (0.046-0.073)	0.079 (0.057-0.117)	0.112 (0.069-0.174)	0.159 (0.075-0.268)	0.212 (0.088-0.366)
	Total Population	455.6	459.6	462.3 (458.3-466.0)	466.1 (451.8-480.4)	466.7 (441.6-494.1)	459.4 (423.0-504.3)	446.6 (391.9-507.9)	389.4 (311.3-489.3)	350.1 (246.9-462.2)
Eastern Europe	*Aver. Age*	37.0	38.4	39.8 (39.6-40.1)	42.7 (41.7-43.7)	45.6 (44.0-47.4)	48.2 (45.6-51.0)	50.3 (46.7-54.1)	52.4 (46.4-59.8)	52.4 (45.3-62.5)
	Prop. 60+	0.18	0.18	0.20 (0.20-0.20)	0.25 (0.24-0.26)	0.29 (0.27-0.32)	0.36 (0.32-0.40)	0.42 (0.36-0.48)	0.44 (0.34-0.56)	0.44 (0.32-0.58)
	Prop. 80+	0.019	0.025	0.031 (0.030-0.031)	0.037 (0.034-0.041)	0.049 (0.041-0.061)	0.076 (0.057-0.107)	0.091 (0.061-0.140)	0.164 (0.086-0.296)	0.185 (0.081-0.356)
	Total Population	121.2	120.6	119.5 (118.7-120.3)	115.6 (112.2-118.9)	109.8 (103.8-116.0)	102.2 (93.1-112.2)	93.4 (81.9-106.7)	71.5 (54.5-92.4)	56.6 (37.4-78.5)

Supplementary Table 1 (continued)

European Soviet Union	*Aver. Age*	37.2	38.5	39.7 (39.5-39.9)	42.3 (41.5-43.3)	45.1 (43.7-46.8)	47.4 (45.0-50.1)	49.1 (45.6-52.8)	50.1 (44.2-56.7)	48.6 (42.5-57.8)
	Prop. 60+	0.19	0.18	0.19 (0.19-0.19)	0.24 (0.24-0.25)	0.29 (0.27-0.31)	0.33 (0.30-0.37)	0.40 (0.34-0.46)	0.41 (0.31-0.52)	0.39 (0.28-0.51)
	Prop. 80+	0.020	0.023	0.031 (0.030-0.031)	0.038 (0.035-0.041)	0.040 (0.034-0.047)	0.068 (0.053-0.091)	0.079 (0.055-0.122)	0.141 (0.072-0.247)	0.143 (0.063-0.292)
	Total Population	235.6	231.5	227.6 (226.1-228.9)	216.7 (210.4-222.8)	203.0 (191.9-214.5)	186.7 (170.7-205.0)	168.2 (146.6-192.0)	129.4 (96.9-165.8)	107.6 (68.1-149.5)
World	*Aver. Age*	29.7	30.4	31.3 (31.0-31.5)	33.1 (32.2-34.0)	35.2 (33.9-36.7)	37.1 (35.3-39.1)	38.8 (36.4-41.4)	42.3 (38.8-46.4)	45.5 (41.1-51.4)
	Prop. 60+	0.10	0.10	0.11 (0.11-0.11)	0.13 (0.13-0.14)	0.17 (0.15-0.18)	0.19 (0.17-0.21)	0.22 (0.19-0.26)	0.27 (0.22-0.34)	0.32 (0.25-0.41)
	Prop. 80+	0.011	0.012	0.013 (0.013-0.013)	0.015 (0.014-0.017)	0.020 (0.017-0.024)	0.029 (0.022-0.040)	0.040 (0.028-0.060)	0.066 (0.036-0.116)	0.096 (0.048-0.190)
	Total Population	6.1	6.4	6.8 (6.7-6.9)	7.5 (7.2-7.8)	8.1 (7.6-8.5)	8.5 (7.8-9.2)	8.8 (7.8-9.9)	8.9 (7.1-10.8)	8.4 (6.2-11.1)

Supplementary Table 2. Six alternative ageing measures (derived from the mean scenario) for all world regions.

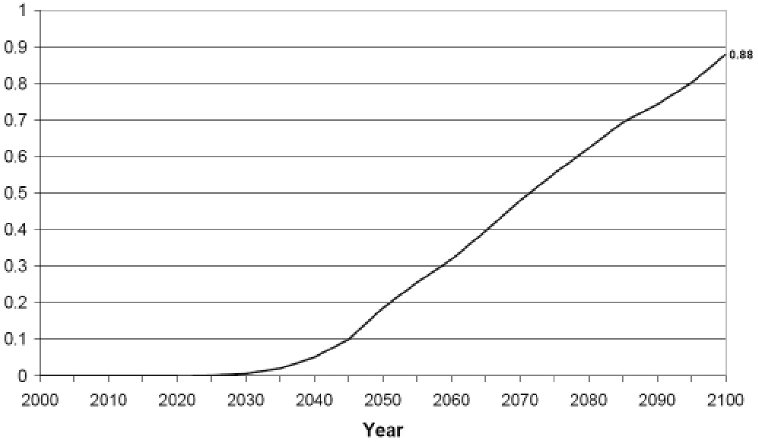
Region	Indicator	2000	2005	2010	2020	2030	2040	2050	2075	2100
North Africa	*Aver. Age*	25.5	26.4	27.3	29.7	32.5	35.2	37.5	41.7	44.6
	Prop. 60+	0.06	0.06	0.07	0.09	0.12	0.15	0.19	0.27	0.31
	PARYL	46.2	46.2	46.1	45.4	44.3	43.4	42.7	42.2	43.2
	MA	21.6	22.9	24.3	26.9	30.0	33.2	36.3	41.2	44.8
	Prop. RLE 15-	0.05	0.05	0.05	0.06	0.07	0.09	0.11	0.14	0.16
	PMA	21.6	22.0	22.6	23.7	25.2	27.1	28.8	30.0	29.3
Sub Saharan Africa	*Aver. Age*	22.1	21.6	21.6	22.2	23.7	25.4	27.3	32.9	38.0
	Prop. 60+	0.05	0.04	0.04	0.05	0.05	0.05	0.07	0.13	0.20
	PARYL	37.7	37.2	36.5	37.7	39.6	40.1	40.1	39.1	38.1
	MA	17.4	17.0	16.9	17.9	20.2	22.2	24.3	30.2	36.8
	Prop. RLE 15-	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.13
	PMA	17.4	18.0	18.8	17.6	16.1	15.9	16.2	16.8	18.1
North America	*Aver. Age*	36.5	37.0	37.7	39.5	41.3	42.6	43.6	46.5	49.5
	Prop. 60+	0.16	0.17	0.18	0.23	0.27	0.28	0.30	0.35	0.39
	PARYL	43.0	43.3	43.4	43.5	43.6	44.1	45.0	46.3	48.4
	MA	35.9	36.7	37.2	38.4	40.3	41.9	43.0	47.0	50.0
	Prop. RLE 15-	0.11	0.10	0.10	0.11	0.13	0.15	0.14	0.15	0.15
	PMA	35.9	35.8	35.4	34.7	34.8	34.6	33.7	33.0	30.9
Latin America	*Aver. Age*	27.8	28.8	29.8	32.2	34.7	37.0	38.9	42.3	44.7
	Prop. 60+	0.08	0.08	0.09	0.11	0.15	0.19	0.22	0.28	0.32
	PARYL	46.4	46.2	45.9	45.1	44.3	43.7	43.5	44.2	45.9
	MA	24.4	25.8	27.2	30.1	32.9	35.5	37.8	41.6	44.6
	Prop. RLE 15-	0.06	0.06	0.06	0.07	0.08	0.10	0.12	0.14	0.14
	PMA	24.4	25.0	25.7	27.1	28.4	29.4	30.1	29.6	28.0
Central Asia	*Aver. Age*	26.9	27.8	28.7	30.7	33.4	35.7	37.9	42.4	46.0
	Prop. 60+	0.08	0.08	0.08	0.10	0.13	0.16	0.20	0.28	0.33
	PARYL	46.4	46.2	46.0	45.4	44.4	43.7	43.2	42.8	43.4
	MA	22.8	24.0	25.3	28.4	31.4	33.8	36.6	41.8	46.4
	Prop. RLE 15-	0.06	0.06	0.05	0.06	0.08	0.09	0.10	0.14	0.16
	PMA	22.8	23.2	23.8	25.6	27.1	28.1	29.4	30.6	30.8
Middle East	*Aver. Age*	24.2	25.1	26.0	28.3	31.4	34.4	37.1	42.6	46.6
	Prop. 60+	0.06	0.06	0.06	0.08	0.10	0.14	0.19	0.28	0.34
	PARYL	48.8	48.8	48.7	48.3	47.0	45.8	44.9	43.5	43.7
	MA	19.9	21.2	22.6	25.5	28.7	32.3	35.9	42.4	47.4
	Prop. RLE 15-	0.04	0.04	0.04	0.05	0.06	0.07	0.09	0.13	0.16
	PMA	19.9	20.3	20.9	22.0	23.5	25.5	27.6	30.0	30.6
South Asia	*Aver. Age*	26.5	27.1	27.8	29.8	32.2	34.6	37.0	42.4	47.3
	Prop. 60+	0.07	0.07	0.08	0.09	0.12	0.14	0.17	0.26	0.35
	PARYL	44.1	44.1	43.9	43.2	42.1	41.2	40.4	38.6	37.6
	MA	22.7	23.4	24.5	26.9	29.6	32.8	35.9	42.6	48.5
	Prop. RLE 15-	0.06	0.06	0.06	0.07	0.08	0.10	0.11	0.16	0.19
	PMA	22.7	22.9	23.4	24.7	26.3	28.3	30.2	33.7	36.2
China Region	*Aver. Age*	31.2	33.2	35.1	38.6	42.3	45.5	47.7	50.7	51.2
	Prop. 60+	0.10	0.11	0.12	0.17	0.24	0.30	0.35	0.41	0.42
	PARYL	43.4	42.1	41.0	39.0	36.9	35.5	35.0	36.1	39.3
	MA	29.6	32.3	34.7	38.5	43.0	47.5	50.7	53.7	54.0
	Prop. RLE 15-	0.07	0.08	0.08	0.11	0.14	0.19	0.21	0.24	0.22
	PMA	29.6	31.7	33.5	36.0	39.3	42.3	44.1	43.0	38.6
Pacific Asia	*Aver. Age*	28.2	29.3	30.5	33.0	35.4	37.6	39.5	43.2	47.5
	Prop. 60+	0.08	0.08	0.09	0.12	0.16	0.20	0.23	0.29	0.36
	PARYL	44.7	44.4	43.9	42.9	42.1	41.5	41.2	41.2	41.1
	MA	25.3	26.9	28.4	31.4	34.0	36.4	38.6	43.3	48.7
	Prop. RLE 15-	0.06	0.06	0.07	0.08	0.10	0.12	0.14	0.15	0.17
	PMA	25.3	26.2	27.1	28.7	29.9	30.9	31.6	32.4	33.7
Japan/Oceania	*Aver. Age*	40.4	41.6	43.0	45.7	47.9	49.7	51.3	54.1	57.7
	Prop. 60+	0.22	0.24	0.27	0.31	0.35	0.40	0.42	0.47	0.51
	PARYL	41.3	41.0	40.6	39.7	39.5	39.5	39.6	41.1	43.0
	MA	40.0	41.3	42.8	46.7	49.9	52.1	53.9	57.6	61.1
	Prop. RLE 15-	0.13	0.13	0.14	0.17	0.18	0.18	0.20	0.21	0.21
	PMA	40.0	40.3	40.9	42.9	44.3	44.6	44.5	43.3	41.7

Supplementary Table 2 (continued)

Western Europe	*Aver. Age*	38.3	39.1	40.1	42.4	44.7	46.8	48.4	51.0	53.5
	Prop. 60+	0.20	0.20	0.21	0.25	0.31	0.34	0.37	0.42	0.46
	PARYL	41.0	41.0	40.8	40.3	39.8	39.6	39.7	41.4	43.5
	MA	36.8	38.3	40.0	43.1	45.8	48.2	50.2	53.5	56.5
	Prop. RLE 15-	0.13	0.13	0.13	0.14	0.15	0.18	0.19	0.20	0.19
	PMA	36.8	37.5	38.3	39.6	40.5	41.1	41.3	39.8	37.7
Eastern Europe	*Aver. Age*	37.0	38.4	39.8	42.7	45.6	48.2	50.3	52.4	52.4
	Prop. 60+	0.18	0.18	0.20	0.25	0.29	0.36	0.42	0.44	0.44
	PARYL	39.7	39.1	38.5	37.3	36.0	35.3	34.9	36.9	40.6
	MA	35.6	37.1	38.9	42.9	47.3	51.3	54.0	55.7	55.7
	Prop. RLE 15-	0.13	0.13	0.13	0.15	0.18	0.19	0.22	0.24	0.21
	PMA	35.6	36.4	37.4	39.9	42.8	45.2	46.3	43.5	38.6
European Soviet Union	*Aver. Age*	37.2	38.5	39.7	42.3	45.1	47.4	49.1	50.1	48.6
	Prop. 60+	0.19	0.18	0.19	0.24	0.29	0.33	0.40	0.41	0.39
	PARYL	37.3	36.9	36.7	35.6	34.4	33.8	33.8	36.7	41.4
	MA	36.4	37.9	39.0	42.4	46.5	50.7	52.4	52.2	50.1
	Prop. RLE 15-	0.14	0.15	0.14	0.15	0.19	0.21	0.22	0.23	0.19
	PMA	36.4	37.0	37.2	39.2	42.0	45.0	45.2	40.8	33.9
World	*Aver. Age*	29.7	30.4	31.3	33.1	35.2	37.1	38.8	42.3	45.5
	Prop. 60+	0.10	0.10	0.11	0.13	0.17	0.19	0.22	0.27	0.32
	PARYL	43.8	43.6	43.3	42.8	42.1	41.6	41.3	41.0	41.2
	MA	26.6	27.5	28.4	30.8	33.2	35.3	37.3	41.4	45.6
	Prop. RLE 15-	0.07	0.07	0.07	0.08	0.10	0.11	0.12	0.14	0.16
	PMA	26.6	27.0	27.5	28.5	29.4	30.4	31.1	32.1	32.9

Supplementary Table 3. Short- and medium-run total fertility assumptions, mean and 80% intervals, 2000-2050.

Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
North Africa	3.3	3.1	2.9 (2.3-3.5)	2.7 (2.1-3.2)	2.4 (2.0-2.9)	2.2 (1.8-2.6)	2.1 (1.7-2.5)	2.1 (1.7-2.4)	2.0 (1.7-2.4)	2.0 (1.7-2.4)	2.0 (1.7-2.4)
Sub Saharan Africa	5.6 (5.3-5.8)	5.3 (5.0-5.6)	4.8 (4.1-5.5)	4.4 (3.7-5.0)	3.9 (3.2-4.6)	3.4 (2.7-4.1)	3.1 (2.4-3.8)	3.0 (2.3-3.7)	2.9 (2.2-3.5)	2.7 (2.1-3.3)	2.6 (2.1-3.2)
North America	2.0	2.0	1.9 (1.6-2.3)	1.9 (1.6-2.2)	1.9 (1.5-2.2)	1.9 (1.5-2.2)	1.8 (1.5-2.2)	1.9 (1.5-2.2)	1.9 (1.6-2.2)	1.9 (1.6-2.2)	1.9 (1.6-2.2)
Latin America	2.6	2.5	2.4 (1.9-2.9)	2.3 (1.9-2.8)	2.2 (1.8-2.7)	2.1 (1.8-2.5)	2.1 (1.7-2.4)	2.1 (1.7-2.4)	2.1 (1.7-2.4)	2.1 (1.7-2.4)	2.1 (1.7-2.4)
Central Asia	2.8	2.7	2.5 (2.0-3.0)	2.4 (1.9-2.9)	2.3 (1.9-2.7)	2.2 (1.8-2.6)	2.1 (1.7-2.4)	2.1 (1.7-2.4)	2.0 (1.7-2.4)	2.0 (1.7-2.3)	2.0 (1.7-2.3)
Middle East	3.7	3.4	3.1 (2.4-3.8)	2.8 (2.2-3.4)	2.5 (2.0-3.0)	2.2 (1.8-2.6)	2.1 (1.7-2.4)	2.1 (1.7-2.4)	2.0 (1.7-2.4)	2.0 (1.7-2.3)	2.0 (1.6-2.3)
South Asia	3.5 (3.3-3.6)	3.1 (2.9-3.2)	2.8 (2.2-3.5)	2.6 (2.1-3.2)	2.4 (1.9-2.9)	2.2 (1.8-2.6)	2.1 (1.7-2.4)	2.0 (1.7-2.3)	2.0 (1.6-2.3)	1.9 (1.6-2.2)	1.9 (1.5-2.2)
China region	1.5 (1.3-1.7)	1.5 (1.3-1.7)	1.5 (1.2-1.7)	1.5 (1.2-1.7)	1.4 (1.2-1.7)	1.4 (1.1-1.7)	1.4 (1.1-1.7)	1.4 (1.1-1.8)	1.5 (1.2-1.8)	1.5 (1.2-1.8)	1.5 (1.2-1.8)
Pacific Asia	2.5	2.4	2.3 (1.9-2.7)	2.3 (1.8-2.7)	2.2 (1.8-2.6)	2.1 (1.8-2.5)	2.1 (1.7-2.4)	2.0 (1.7-2.4)	2.0 (1.7-2.3)	1.9 (1.6-2.3)	1.9 (1.6-2.2)
Japan/Oceania	1.4	1.3	1.3 (1.0-1.7)	1.4 (1.0-1.7)	1.4 (1.1-1.7)	1.4 (1.1-1.8)	1.4 (1.1-1.8)	1.5 (1.1-1.8)	1.5 (1.2-1.8)	1.5 (1.2-1.8)	1.5 (1.2-1.8)
Western Europe	1.7	1.5	1.5 (1.2-1.8)	1.5 (1.2-1.9)	1.5 (1.2-1.9)	1.5 (1.2-1.9)	1.5 (1.2-1.9)	1.6 (1.3-1.9)	1.6 (1.3-1.9)	1.6 (1.3-1.9)	1.6 (1.3-2.0)
Eastern Europe	1.4	1.3	1.3 (1.0-1.7)	1.4 (1.0-1.7)	1.4 (1.1-1.7)	1.4 (1.1-1.8)	1.5 (1.1-1.8)	1.5 (1.2-1.8)	1.5 (1.2-1.8)	1.5 (1.2-1.8)	1.6 (1.2-1.9)
European Soviet Union	1.3	1.3	1.3 (1.0-1.6)	1.4 (1.0-1.7)	1.4 (1.1-1.7)	1.4 (1.1-1.8)	1.5 (1.1-1.8)	1.5 (1.2-1.8)	1.6 (1.2-1.9)	1.6 (1.3-1.9)	1.6 (1.3-2.0)



Supplementary Figure 1. Probability that the world's population will reach a peak by the indicated date.

The Uncertain Timing of Reaching 8 Billion, Peak World Population, and Other Demographic Milestones[1]

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Trends in the populations of countries, regions, or the world are often characterized by the dates at which they reach certain demographic milestones. In 2006 the United States recorded a population of 300 million, and last year the European Union (EU-27) reached 500 million. Future trends in population are also often characterized according to the date at which they are expected to reach certain round numbers. But the timing of demographic milestones is uncertain, not only when they refer to the distant future, but also when they are nearer to hand. This is partly because of uncertainties about current demographic conditions in areas of the world with unreliable statistical in- formation and partly because of the inherent uncertainty about future rates of fertility, mortality, and migration. Population forecasts should adequately reflect such uncertainties. The practice of producing high, medium, and low variants based solely on alternative fertility assumptions is deficient in this respect. The lack of significant uncertainty in future mortality trends makes the high and low variants useless for forecasting indicators referring to the size of the elderly population. Migration tends to be the most volatile of the demographic components, and its uncertain future levels can matter greatly for the size of the labor force. Information about the possible uncertainty of current conditions is also disregarded. Probabilistic forecasts, on the other hand, are an appropriate tool that incorporates all of these uncertainties. They are also richer than conventional probability-free projections or scenarios since they provide quantitative uncertainty stributions for important demographic variables.[2]

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[2] Probabilistic population forecasts seek to quantify the uncertainty range of projected values of future demographic parameters. This is different from giving alternative but probability-free scenarios of a high-medium- low range of projections that are said to cover a plausible range. In addition to quantifying the uncertainty in numerical terms, probabilistic forecasts also have the advantage of simultaneously reflecting uncertainty in the future paths of fertility, mortality, and migration. The UN high and medium ranges, for instance, reflect only the range implied by alternative fertility assumptions, thus disregarding uncertainties related to mortality and migration in future trends. Comprehensive re- views and discussions of different approaches to probabilistic population projections are given in two special issues of the International Statistical Review (Lutz & Goldstein 2004) and in a supplement to Population and Development Review (Lutz et al. 1999, p.199).
The specific probabilistic forecasting approach applied here is described in detail in Lutz, Sanderson, and Scherbov (2004). It is based on thousands of simulations in the form of individual cohort component projections drawing randomly from uncertainty distributions of future fertility, mortality, and migration levels. It is done at the level of 13 world regions (following the definitions used in the intergovernmental Panel on Climate Change scenarios) assuming certain regional and temporal correlations. The assumed uncertainty distributions of the three components in the different world regions were defined and substantively argued by distinguished experts in the respective fields (for further details, see Lutz et al. 2004). in the projections described here, these assumptions about future fertility, mortality, and migration in different parts of the world have been combined with the new un 2010 estimates of baseline conditions in 2010. The results are presented in terms of the regional distributions resulting for certain demographic indicators (population size and age structural indicators) from the set of simulations described above.

Probabilistic demographic forecasts have recently become more widely used not only by researchers (Ahlo et al. 2008; Keilman et al. 2002; Lutz et al. 2008; Tuljapurkar & Lee 2000) but also by statistical offices (Heilig et al. 2010; SSA 2010; Statistics Netherlands 2005). Until now most probabilistic forecasts were concerned with the uncertainty distributions of demographic variables at a specific point in time. But probabilistic forecasts can also be used to estimate the distribution of possible dates at which particular well-defined demographic milestones are likely to be reached.[3]

An important global demographic milestone has recently received public attention, the date at which the world's population would reach 7 billion (National Geographic 2011; United Nations 2011a). The united nations, on the basis of its 2008 assessment, had originally forecasted that this would occur on 26 August 2011 (United Nations 2010). The most recent 2010 assessment (United Nations 2011b) postpones this date to 31 October 2011. Our recent probabilistic forecasts (Lutz et al. 2008), based on 2005 baseline estimates that took some baseline uncertainty into account, resulted in a modal forecast of the day of 7 Billion occurring in July 2012, and a median forecast of its occurring in January 2013, with a 60 percent prediction interval between February 2012 and July 2014. This uncertainty about the exact date of reaching the 7 billion mark is due to significant uncertainties about current population sizes in Africa, where many countries have conducted no recent censuses; and in the two demographic giants, India and China, where significant concern has been raised about the coverage of recent censuses and about the accuracy of current fertility levels (Ren et al. 2009).

More generally, all demographic projections suffer from two kinds of potential errors: errors resulting from incorrect or incomplete empirical information about recent

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[3] The main difference between the results of the 2010 UN Revision and the 2008 UN Revision is in the procedure for making assumptions about future fertility rates. The 2008 UN Revision used four deterministic models of the relationship between the level of the total fertility rate and its change over a five-year period. An important assumption was that, in the long run, medium-variant total fertility rates for all countries will converge at 1.85. In the 2010 UN Revision, the medium-variant fertility rates were the median of 100,000 simulations of a Bayesian hierarchical statistical model, with the assumption that, in the long run, total fertility rates will converge at 2.1 (Raftery et al. 2009). A significant fraction of the difference between the outcomes from the 2008 and 2010 Revisions results from the difference in the assumption about the ultimate levels at which total fertility rates will converge.

The Bayesian hierarchical model also substantially increases the variance of forecasted total fertility rates in 2045–50. This is especially true for countries with relatively high total fertility rates. For example, the forecasted total fertility rate for Nigeria in 2045–50 rose from 2.41 children in the 2008 Revision to 3.41 in the 2010 Revision. At the same time, the forecast for Germany's total fertility rate increased from 1.69 to 1.87. Most of the difference in the results between the 2008 and 2010 Revisions comes from the large increases in forecasted fertility rates of today's high-fertility countries.

In the 2008 Revision, a large number of countries were kept at the medium-variant boundary of 1.85 in 2045–50. They included Bangladesh and Bhutan. In the 2010 Revision, this boundary was relaxed. As a result the medium-variant total fertility rates for those two countries in 2045–50 were forecasted as 1.58 and 1.56. Both are well below the forecasted total fertility rate of Germany at that date.

In making forecasts, there is no substitute for the use of critical judgment. In the 2010 Revision, the UN shifted the locus of those judgments from ones having a direct connection to fertility rates to those having to do with complex interactions of various statistical distributions and assumptions. Our preference is for a more transparent procedure for setting assumptions, in which clear reasons are given for the assumptions made.

population size, structure, and current vital rates (base-line errors) and errors resulting from uncertainty about future trajectories of fertility, mortality, and migration. Typically, for statements about the near-term future, such as the day of 7 Billion, the baseline error is more relevant whereas for the long term, errors in vital rates carry more weight. At this point we should note that the increase in projected population sizes in the UN 2010 assessment (United Nations 2011b) as compared to the 2008 assessment (United Nations 2009) is almost entirely a function of changes in assumptions about future fertility levels. The estimate of global population growth for the period 2005–2010 was revised downward from the 2008 to the 2010 assessments. The average annual population increment for this period was lowered from 79.4 million to 76.8 million, the annual population growth rate was reduced from 1.17 percent to 1.16 percent, and the global TFR fell from 2.56 to 2.52. These are minor downward adjustments, and such adjustments are regularly made when new information becomes available. But the new higher population projections resulting in a population of more than 10 billion sometime during this century are not based on higher-than-expected population growth in the recent past but only on a new set of assumptions about future fertility.

In this short note we present a new set of projections that combine the baseline data of the un 2010 assessment for all countries (for population size, age structure, and vital rates) with the probabilistic assumptions of our 2008 projections (Lutz et al. 2008) concerning future regional and global trends.[4] We present the results in a novel way that focuses on the uncertainty of the timing of reaching three milestones further in the future: the day of 8 Billion, the date at which one-third of the population will be aged 60+, and the date of reaching the world's peak population. The uncertainty in these forecasts stems entirely from the uncertainty of future paths of fertility, mortality, and migration, since no baseline error is allowed.

Figure 1 shows our forecasted cumulative probability of the date at which the world's population will reach 8 billion people. The median date is 2027. The medium variant of the 2010 United Nations forecasts yields a date of 15 June 2025 (United Nations 2011a). Our 60 percent prediction interval lies between 2024 and 2033. There is a 10 percent chance that the day of 8 Billion will occur after 2039. The UN's high and low variants provide a range between 2022 and 2035. According to our figures, there is around an 83 percent chance that the day of 8 Billion will occur between those years.

Figure 2 shows the cumulative probability of the date at which one-third or more of a population becomes 60+ years old. By 2100, that probability reaches almost 60 percent for the world as a whole. The median date of that event is 2025 for the Pacific/Oceania region, 2040 for Western Europe (including Turkey), and 2072 for North America.[5] The steepness of the slope of the cumulative probability indicates that prediction intervals for the dating of that milestone are relatively compressed for Pacific/Oceania and considerably wider for North America. The 60 percent prediction interval lies between 2023 and 2028 for Pacific/

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[4] We made an exception in applying the assumptions of our 2008 projections in the case of mortality rates in sub-Saharan Africa, because of the decline in the severity of the HIV/AIDS epidemic in that region. We use UN mortality rates to 2050 and thereafter use the same increase in life expectancy at birth that we used in our previous forecasts.

[5] The regional definitions used here follow those in the IPCC-SRES (Special Report on Emission Scenarios) scenarios (see detailed definition in Lutz et al. 2004). Pacific/Oceania includes 3 countries, Australia, New Zealand, and Japan. We have two other differences with the standard UN regions. Our Western Europe includes turkey, and our North Africa includes Sudan, which the UN places in sub-Saharan Africa.

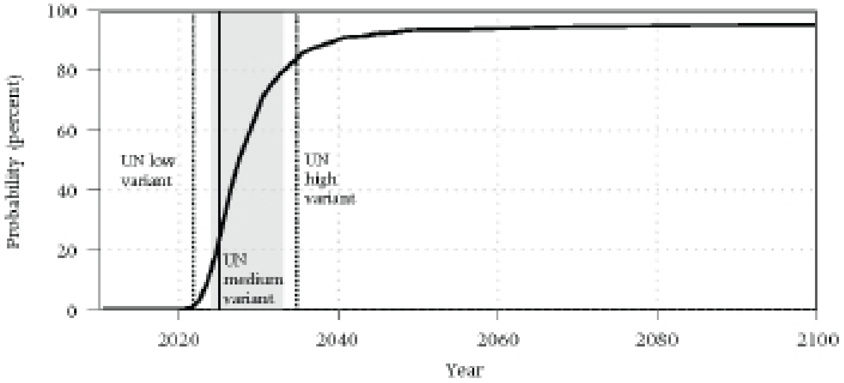

Figure 1. Cumulative probability of the date at which world population reaches 8 billion, based on probabilistic projections taking the UN 2010 assessment as baseline data

Note: The date at which world population reaches 8 billion according to the UN low, medium, and high variants is indicated by vertical lines. Shading indicates our 60 percent prediction interval, which lies between 2024 and 2033.

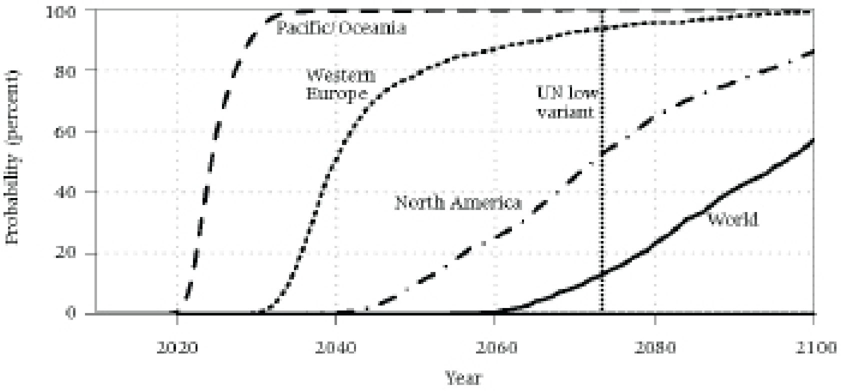

Figure 2. Cumulative probability of the date at which one-third of the population is aged 60+ years, based on probabilistic projections taking the UN 2010 assessment as baseline data

Note: The date at which one-third of world population is aged 60+ according to the UN low variant is indicated by a vertical line.

Oceania and between 2056 and 2094 for North America. The UN low, medium, and high variants are inappropriate for the study of the uncertainty of measures of aging because they are based solely on differences in fertility and ignore possible future variability in mortality. Nevertheless, the vertical line in Figure 2 indicates the date at which the world reaches the aging milestone according to the low variant. In neither the medium nor the high variant does the proportion of the world's population aged 60+ reach 33 percent by the end of the century.

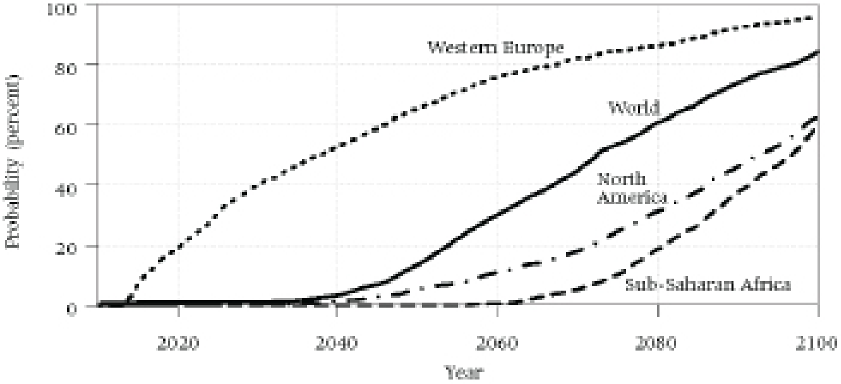

Figure 3. Cumulative probability of the date at which the world and regional populations reach a peak followed by a decline, based on probabilistic projections taking the UN 2010 assessment as baseline data

Figure 3 shows the cumulative distribution of the date at which the world's population will peak, derived from our new probabilistic forecast using the 2010 UN baseline and our assumptions about the future. We also provide forecasts for sub-Saharan Africa, Western Europe, and North America. This demographic milestone is not just the reaching of one specific world population size, because the date at which world population size peaks can occur at different levels and different times for individual random trajectories.

The cumulative probability of the world's population peaking by a given year has roughly a constant slope from 2050 onward, indicating that the probability of peaking is roughly the same throughout the half century from 2050 to 2100. The probability of a peak population being reached during the century is around 84 percent. (For North America the probability is lower – 60 percent – on the assumption of continued population growth resulting in part from net immigration.) The 60 percent probability interval for reaching the world's peak population is between 2054 and 2097. Therefore, while there is little uncertainty that world population will peak and start to decline before the end of the century, there is great uncertainty about when during the second half of the century this peak population will occur. The figure also indicates a 50 percent chance that the population of Western Europe will reach a peak by 2038, the world's population will peak by 2072, North America will peak by 2093, and sub-Saharan Africa will peak by 2097. As we mentioned earlier, however, these data must be considered along with the associated uncertainties; otherwise they convey a false sense of precision.

One surprise in the UN's 2010 population forecasts is the absence of a peak in the medium-variant forecast of the world's population during this century. a discussion of the peak fi appeared in Lutz, Sanderson, and Scherbov (2001) and was subsequently included in the un long-range forecasts published in 2004 (United Nations 2004), based on different assumptions. It was widely believed that a peak would be evident in the medium-variant 2010 forecasts, the first since the 2004 forecasts to extend to the year 2100. The absence of a peak is largely due to changes in the assumptions made about future fertility in sub-Saharan Africa between the UN's 2008 and 2010 assessments.

In this note, we have conveyed a sense of the uncertainty of the dating of demographic milestones. The marking of certain demographic milestones, such as the day of 7 Billion, focuses public attention on the issues of population growth, shrinkage, and age-structure change. This is an opportune occasion to promote public understanding of the demographic forces shaping our societies. A problem arises because, in the process of providing exact dates for demographic milestones, we ignore the true extent of our ignorance. From the viewpoint of demographic science, clearly communicating the uncertainty of our forecasts would be a step forward.

But the uncertainty of demographic milestones is not a constant of nature. It depends on the intellectual and financial resources that we devote to collecting and analyzing data and to producing better analysis and forecasting methodologies. Understanding the extent of our uncertainty could help motivate governments and other organizations to make the efforts needed to produce better forecasts and reduce uncertainty. In a sense, the reduction of uncertainties about future events has always been the primary goal of science. To achieve this goal, we need to address existing uncertainties rather than ignore them.

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Expert-Based Probabilistic Population Projections[1]

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Most users of population projections are interested in one likely path of future population trends based on the best existing knowledge. Whether it is called the medium variant, central scenario, or median of an uncertainty distribution, this projected path will be taken as a forecast on which further considerations can be based. For many users such a best guess will suffice. It can be taken as an exogenous input into their own models for school planning, social security considerations, energy outlook, and the like. For this reason a medium projection is an indispensable component of any set of published projections intended for practical use.

Different ways to deal with uncertainty

Variants

User concern about the uncertainty associated with population projections has led many statistical offices and the United Nations to produce and publish not only a medium variant but also high and low variants. Typically these high and low variants differ from each other and from the medium variant only in terms of fertility assumptions. Mortality and migration assumptions tend to be identical. This approach is being increasingly criticized and a number of statistical offices now publish alternative mortality variants. An additional problem arises when aggregating the national-level projections to regional or global projections; the high and low variants are calculated in such a way that the high and low fertility assumptions are assumed to be simultaneously prevalent in all individual countries. Since in the real world one would expect a great deal of canceling (trends above expectation in one country and below expectation in others), the global high variant as published by the United Nations is much less probable than the high variant in any particular country.

The real problem with the variants approach is that the user is not told how to interpret the variants. Nowhere in the publications themselves or elsewhere in the demographic literature can one find exact definitions of such "variants." Are they just sample paths, or do they demarcate certain ranges? The notion of a plausible or probable range is sometimes used, but not unambiguously defined.[2] It is sometimes explicitly stated that variants should *not* be interpreted as giving any sort of confidence intervals in a probabilistic sense. But this is exactly what most users take them to be because an uncertainty distribution is the logical interpretation of any set of "high," "medium," and "low" trends plotted over time. To an informed non-demographer – a scholar from another scientific discipline, who is unfamiliar with the traditional practice of demographers – an immediate question will be whether the range given by the variants is assumed to cover 100 percent, 90 percent, or any other

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[2] The United Nations (United Nations 1995, p.143) gives the following interpretation of its variants: "The high-, medium- and low-fertility variants for each country are all thought to pro vide reasonable and plausible future trends in fertility. The low- and high-fertility variants are usually thought to bracket the probable range of future population change for each country; nevertheless, the fertility change for a given country could progress, and occasionally has, at a pace outside the high-low bracket."

proportion of all possible future paths. But the demographic producers generally refuse to be precise about their subjective probability distribution, and do not give the user a satisfactory answer to this crucial question. What should the user do with the variants if he is not clearly told how to interpret them?

Scenarios

There are two ways to overcome these problems associated with the traditional variants approach. The first approach is to explicitly call the alternative projections "scenarios" designed to demonstrate the consequences of certain specified conditions. Originally the word "scenario" comes from the theater. The *Oxford English Dictionary* (OUP 1982) defines it as, "A sketch, outline, or description of an imagined situation or sequence of events." During the 1970s and 1980s the word "scenario" became popular in the social sciences, especially in the context of computer models (Lutz 1995). In the realm of population projections, the term is used with two somewhat different meanings: 1) in the sense of purely hypothetical assumptions, for example, a "constant fertility scenario"; and 2) in the sense of a consistent story in which fertility, mortality, and migration assumptions are embedded to provide a comprehensive picture of what the future might be. While the second usage is certainly closer to the original meaning in terms of a consistent picture, the first has gained great popularity.

In both usages of "scenario" specific assumptions have a defining role and are spelled out prominently, often in the name of the scenario. Neither usage addresses the probability of the assumed sequence of events. Scenarios need to be conceivable but not likely. A constant fertility scenario in all countries of the world is certainly extremely unlikely but it cannot be entirely ruled out on theoretical grounds. Its publication clearly serves a purely educational purpose.

Other examples of population scenarios that follow a more consistent story are given in Lutz (1996) for specific world regions: The "African Food Crisis Scenario," for instance, assumes that there will be a serious mortality crisis in sub-Saharan Africa (killing 20 percent of the population) when an assumed carrying capacity of 2.5 billion people is reached. The United Nations could specify a scenario that would demonstrate the long-term impacts of successful implementation of the quantitative goals of the "Cairo Programme of Action" in the fields of health and unmet need for family planning. The current "low" variant of the UN projections certainly does not reflect such a scenario since it does not assume extra efforts in health.

Probabilistic projections

The other way to overcome the problems associated with variants is to systematically consider possible deviations from the most likely path for all three components. This can be done by applying errors from past population projections or making assumptions about variance derived from past time series, or alternatively by having experts define ex ante probability distributions. While most of the literature on probabilistic population projections follows the first approach (Lee 1999; Lee & Tuljapurkar 1994; Lee & Carter 1992; Lee 1993; Alho 1990; Alho & Spencer 1985; Keilman & Cruijsen 1992), the present chapter will develop the second approach and discuss its theoretical consistency, robustness, and practical applicability.

Expert opinion

With natural phenomena of not too great complexity, the laws of physics can be used to make predictions. They can predict with high precision what time the sun will rise tomorrow and even the exact date of the next total eclipse for a specific place on earth. Since the planets have shown movements of the same structure for millions of years and there is no reason to assume a structural discontinuity in the near future, statements of their future movement come close to what might be called an objective prediction. This is quite different from forecasting more complex natural processes such as the weather. Here the system is not yet well enough under stood and seems to have inherent chaotic components that make it impossible to produce reliable long-term forecasts. Under stable climatic conditions, past time series data can, however, provide us with some in formation about the variance of the system that can be a basis for assuming a reasonable range of uncertainty, for example, for July temperatures in a certain place. But what about climate change? Analyses of ice cores show that there have been instances during which major global climate changes occurred within a couple of decades. Presently, there are strong indications that the climate might change as a result of anthropogenic green house gas emissions, but it is not at all clear how and when. Under such uncertainty, how should temperature and precipitation be forecast for a given region for the middle of the next century? Calculating confidence intervals for humidity purely based on observations of the past decades is probably not a good idea. But how can we do better?

The examples above were chosen from the presumably "exact" natural sciences. But future demographic trends are largely determined by social behavior, which tends to be more complex, even chaotic and much less understood, with no good models even for some basic issues. In contrast to technical or physical systems, we often do not know with a high degree of confidence how society will react to certain events, or why people make certain decisions. With widespread social changes occurring in different parts of the world at an accelerating speed, demographic projections made under the assumption of a constant "climate" may not be very meaningful. In addition, projections based on past time series are impossible for the majority of countries in the world that do not have such series.

There is no objective way to derive confidence intervals

Leaving the above-mentioned problems aside, let us consider the special case of a country that is assumed to have completed its demographic transition, has good and long demographic time series data, has exhibited relatively stable trends over the last three decades, and where no obvious structural change is expected. The United States is such a case; it has the highest number of published probabilistic population projections based on different time series models. Table 1 lists some of these projections for the population around the year 2065. The lower bound of the 95 percent confidence interval ranges from 207 million to 55 l million people. The upper bound ranges between 349 million and 836 million.

The inconsistencies in this table are clear. Pflaumer (1988; 1992), using a time series approach with the logarithm of population as the variable to be explained, is 95 percent confident that the US population around 2065 would lie between 551 and 836 million people. The US Bureau of the Census (1989) is 95 percent confident that the US population in 2065 will lie between 207 and 456 million people. Clearly, both cannot be correct. For example, we cannot simultaneously believe that the probability of the population being 551 million or less is 2.5 percent and the probability of its being 456 million or less is 97.

Table 1. Forecasts and 95 percent confidence intervals (CI) for the population (in millions) of the United States around 2065

Forecaster	Population around 2065	Lower bound of 95% CI	Upper bound of 95% CI
US Bureau of the Census 1989	296	207	456
Pflaumer 1988	301	253	349
Lee and Tuljapurkar 1994	398	259	609
US Bureau of the Census 1992	413	268	599
Pflaumer 1992 (1)[a]	443	270	611
Social security 1989	324	272	389
Social security 1991	351	291	435
Pflaumer 1992 (2)[b]	680	551	836
Logarithmic estimate	620	552	701

Note: Estimates are in ascending order of the lower bound of the 95 percent confidence interval.
[a] ARIMA process with population as dependent variable.
[b] ARIMA process with log(population) as dependent variable.
Source: Lutz, Sanderson, and Scherbov (1996, p.402).

5 percent. Clearly these projection results are, in the end, the responsibility of the experts who make them.

This example demonstrates that even with good data and a large number of alternative projections there is no natural or objective way to derive the future uncertainty in demographic trends from the past. Expert opinion inevitably produces estimates at many different levels. There is no way around expert opinion, which by its nature contains significant subjective aspects. Once this has been accepted the crucial question becomes: what is the best way to convert expert opinion, together with the empirical information about past trends, into assumptions about future uncertainty distributions of the three demographic components, fertility, mortality, and migration?

How to improve on expert opinion

Reliance on expert opinion has many problems at different levels. The first questions are who is considered an expert and what are the criteria for selecting a group of experts to specify future assumptions. The second problem is that even highly qualified and well-respected experts are never entirely free of personal bias. This is even more of a problem if the area for which their advice is sought is not their main field of expertise. Persons who are renowned experts in one field frequently make undifferentiated and unscientifically based statements on other issues that the public or the producer of projections may consider part of their broader field of expertise. A final problem is that most experts (as probably most people) tend to think "conservatively" in terms of structural continuity of the most recent trends, leaving out the possibility of structural discontinuities, even if they become very likely.

An applicable non-demographic example of this continuity bias is the oil price projections that have been produced continuously since 198l by the International Energy Workshop organized by the International Institute for Applied Systems Analysis (IIASA) and Stanford University (Lutz 1995). The time series of projections demonstrates that this group of the world's leading experts tends to extrapolate the most recent trend. They were evidently so thoroughly impressed by the rapid increase in the oil price between 1970 and 1980 that even many years after the price had fallen steeply (and subsequently remained very low) they still projected significant future increases well above the 1980 level, assuming that the decline was only temporary. Only in 1992 did the expert group finally project that oil prices would stay at a relatively low level over the coming decades.

The field of population projections offers many less extreme examples of changing assumptions, especially concerning fertility assumptions before and after the baby boom. But also in the field of mortality, the United Nations assumptions about maximum life expectancy (see Bucht 1996) – which result from extensive interagency consultations – needed to be increased by ten years of life expectancy within only 15 years (1973 to 1988) because observed life expectancies in the most advanced countries were likely to surpass the assumed absolute limits.

Are there any remedies for these problems with expert opinion? Based on a study of the relevant literature on Delphi methods and group dynamics and some commonsense intuition that clearly requires further validation, we proposed two strategies that can be applied simultaneously: 1) ask experts to define a range instead of only a best guess; and 2) expose the experts to an interactive group discussion in which alternative views are challenged and discussed on the basis of substantive arguments.

As to point 1), surprisingly most of the extensive literature on Delphi methods looks only at the case of each expert giving one best guess. But it is conceivable that the misjudgment on future oil prices would have been less serious had the experts been asked to give an uncertainty range rather than one number. In that case the possibility of the oil price remaining around its then prevalent level would at least have been considered, even if assigned low probability. Forcing an expert to settle on a single value may produce a dogmatic reaction rather than fostering the creative doubts that might be better expressed through an uncertainty distribution.

As to point 2), in science a majority of experts is not necessarily right. For this reason an interactive group process challenging dominant wisdom is essential. Such a process must ensure that deviant minority views are given proper space and require the other experts to respond to them in a rational manner. Especially if the issue concerned, such as future fertility and mortality levels, calls for mental flexibility and does not involve strong vested interests, such reasoned argumentation may well lead to a different (and better) consensus about the range of uncertainty than the sum of individual views absent group interaction.

The probabilistic population projections for different world regions to be outlined in the following section incorporate these two strategies. Un certainty distributions for future fertility, mortality, and migration trends in all world regions were defined through interactive discussion by a group of experts who had to support their views through arguments published in scientific papers (for a detailed description, see Lutz 1995). A systematic study of the most appropriate ways for deriving consensus about uncertainty distributions in interactive group settings is ongoing.

Expert opinion is not something to accept uncritically. Minimizing some of the possible biases discussed above calls for rigorous procedures to challenge expert views and tools to evaluate their appropriateness in the light of existing evidence and consistency with plausible hypotheses of future trends in the non-demographic world. Time series analysis may present an important tool for informing and guiding expert choices about the assumptions to be made on future fertility, mortality, and migration trends.

Application and presentation of results

In this section we illustrate the feasibility of the probabilistic projection model and show various ways to present the resulting probabilistic distribution to the benefit of the users. The substantive content of the projections is documented in Lutz (1996).

IIASA has applied the expert-based probabilistic population projection approach to 13 world regions and to some individual countries. The approach evolved from the common practice of statistical agencies of de fining low, medium, and high values for different demographic components. If these assumptions are accepted as expert opinion, the only additional expert judgment necessary is to determine what percentage of all possible future trends should be covered by the high-low range. In the case of the world projections presented here, it was determined that the high-low range for 2030 should cover roughly 90 percent of all possible values for that year.

Technically, the model is simple. Based on the expert-defined assumptions for each region, a normal distribution of fertility, mortality, and migration rates for 2030-35 was specified (see description in Lutz 1996). For each region 1,000 independent cohort-component projections were per formed based on fertility, mortality, and migration rates randomly chosen from the given distribution for 2030-35. The paths between the starting year 1995 and 2030-35 were derived by piecewise linear interpolation in which the range opened up very quickly during the first five-year period in order to avoid too narrow a range at the beginning. After 2030-35 the selected trends were assumed first to weaken and then to level off (see Lutz 1996 for specific assumptions).

This set of 1,000 independent simulations for each region resulted in distributions for total population size and many age-distributional variables. These full distributions of the resulting population for all age groups and projection steps over time exist on an output data base that contains too much information to print in full. It is, therefore, meaningful to characterize the output distributions through fractiles. Table 2 gives, for all world regions for 2050, the median of the resulting distribution and the percent age above age 60 as well as 2.5 percent and 97.5 percent fractiles (i.e., the 95 percent intervals). Figure 1 plots the evolution of six fractiles of the population of North Africa over time. Both approaches condense the information into easily digestible form. Alternatively, the full distribution can be used to answer such specific questions as: what is the probability that the population size of North Africa will double before 2050? or, in the con text of social security, what is the probability that the proportion of the population above age 60 in Western Europe will surpass 30 percent over the next three decades? These are questions that conventional population projections are unable to answer.

Figure 2 presents selected fractiles of the uncertainty distribution for individual age groups for a given year (2030). The results for expert-based probabilistic projections for an individual country, Austria, have been chosen, because in this case the projection could be performed at the level of single years of age instead of the five-year age groups used for the 13 world regions. Figure 2 illustrates the different degrees of uncertainty by age. In 2030 uncertainty is lowest for the age groups SS to 7S years, that is, the cohorts born between 1975 and 1955. Above age 75 uncertainty about future old-age mortality trends results in broader ranges between the fractiles. Between ages 35 and 55, that is, cohorts born 1995 to 1975, the range is significantly broader because of the uncertainty of future trends in migration, which concentrates at younger ages and is quantitatively very significant for Austria. For ages below 35, fertility uncertainty is added to migration uncertainty, and for

Table 2. Results of probabilistic projections for 13 world regions

	Total population (millions)				Population above age 60 (in percent)			
		2050				2050		
Region	1995	Median	2.5%[a]	97.5%[a]	**1995**	**Median**	**2.5%[a]**	**97.5%[a]**
Africa								
North Africa	162	439	309	583	5.9	13.3	9.4	19.2
Sub-Saharan Africa	558	1,605	L085	2,316	4.7	9.2	6.9	12.8
East Asia								
Central East Asia	1,362	1,865	1,351	2,574	9.2	24.9	17.8	34.1
Pacific Asia	447	796	579	1,047	6.8	19.4	14.4	26.5
Pacific OECD countries	147	146	117	182	19.4	39.5	31.5	48.7
West Asia								
Central Asia	54	137	88	206	7.8	15.4	10.2	24.0
Middle East	151	515	380	692	5.4	12.5	9.1	17.3
Southern Asia	1,240	2,368	1,833	2,970	6.7	16.6	13.4	20.8
Europe								
Eastern Europe	122	110	86	141	16.7	34.0	26.7	43.4
Former Soviet Union (European part)	238	188	144	241	16.9	34.l	26.3	44.5
Western Europe	447	471	370	584	18.6	35.0	27.5	43.9
Latin America	477	925	707	1,177	7.6	20.4	15.8	26.4
North America	297	403	303	534	16.4	30.2	24.0	38.6

Note: Fertility, mortality, and migration are assumed to be independent.

[a] Columns labeled 2.5% and 97.5% provide data on the lower and upper bounds, respectively, of the 95 percent confidence interval. Source: Lutz, Sanderson, and Scherbov (1997, p.804)

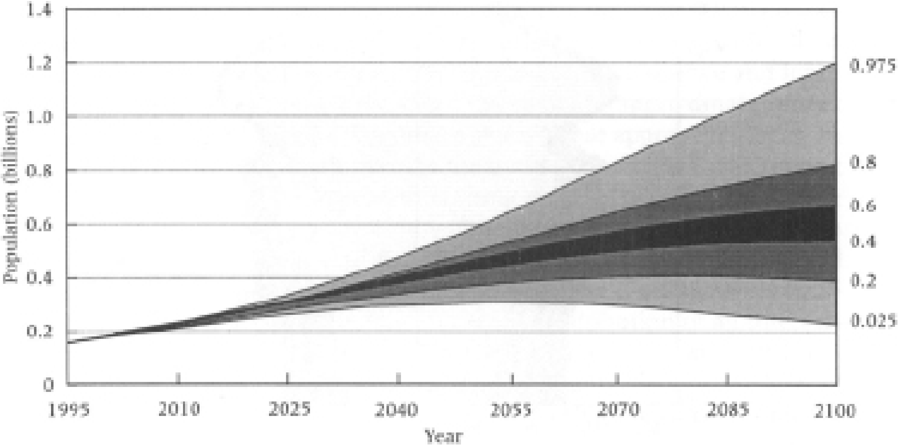

Figure 1. Future population size in North Africa. Figures on the right hand side refer to the probability that the population size will lie below the line indicated

Source: Yousif, Goujon, and Lutz (1996, p.77).

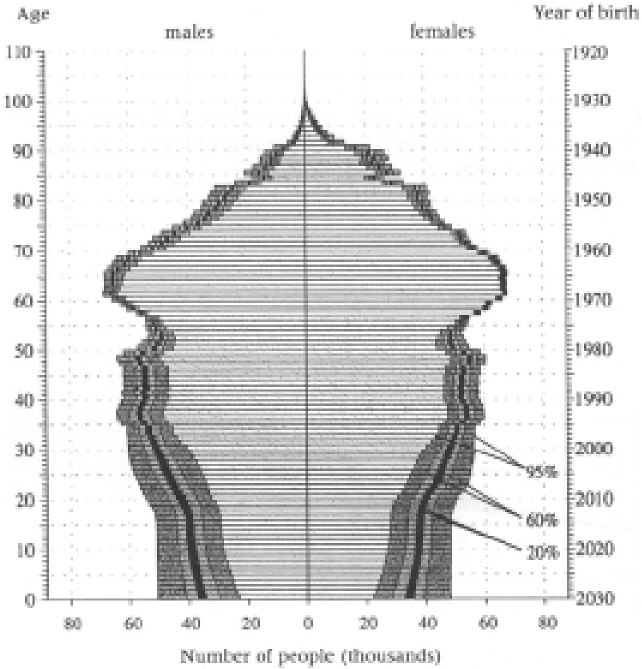

Figure 2. Selected fractiles of the probability distribution of the Austrian age pyramid in 2030

Source: Lutz, Scherbov, and Hanika (1997, p.5).

the youngest ages even the fertility uncertainty of the second generation becomes relevant, resulting in very broad uncertainty ranges.

Finally, the probabilistic projection concept described here also enables the expert to deal with the problem of aggregating projections of different regions, as discussed above for the traditional variants approach. For calculating global aggregates it is no longer necessary to make the highly unlikely assumption that all countries (regions) simultaneously follow the highest or lowest uplausible” path; rather one can define any desired degree of correlation between the fertility, mortality, and migration distributions across countries (regions). In addition, it is also possible to make assumptions on possible correlations, for example, between fertility and mortality for a country in the middle of demographic transition. Results look very different for different assumed correlations. Across regions, for instance, the assumption of independence of trends results in a much narrower un certainty range of future population size than in the case of perfect correlation, because a fertility level above the median in one region may be compensated by below-median fertility in another.

Sensitivity to assumptions and applicability

A number of questions need to be addressed if the approach to expertbased probabilistic population projections presented here is to be generally recommended to statistical agencies for improving their population projection practices. These questions have to do with 1) the sensitivity of the results, especially with respect to the range of uncertainty to be covered by the high-low span; 2) whether the assumed piecewise linear trends in the vital rates underestimate the variance in comparison to assuming an autoregressive model of short-term fluctuations; and 3) institutional questions and issues involved for statistical agencies wishing to adopt this approach.

Sensitivity to alternative distributional assumptions

There is no clear consensus in the scientific literature as to whether experts are particularly good or bad at estimating fractiles of a distribution. In decision analysis common practice is to focus on the median and derive distributions from the question of whether people would be willing to bet money on the outcome being below or above a certain value, which then is modified until people become indifferent. In cognitive science and fuzzy analysis, on the other hand, people talk more about approximate ranges and tend to disregard specific threshold values. These approaches focus on the implicit uncertainty distribution in the mind of one individual. Teasing out the collective distribution of an interacting group of people is even more complex. Most of the literature in this field has focused on aggregating a number of best guesses into one distribution that tends to be highly skewed because of dominating knowledge. The question here is qualitatively completely different: it asks for the joint consensus distribution of an interacting group of experts. All of the distributions derived so far under this approach have turned out to be symmetric, probably mainly for lack of convincing alternatives. But theoretically any other specific distribution could also be implemented under this approach. The two major questions remaining in this context were whether a uniform distribution would be more appropriate than a normal distribution, and whether the experts really can distinguish between 85 percent, 90 percent, and 95 percent of all possible cases assumed to be covered by the high-low range.

Since there seems to be no way to evaluate these questions on a theoretical basis or based on the findings of other scientific disciplines, one way to resolve the issue is to conduct sensitivity analyses to see whether alter native assumptions make much difference in the results. Sensitivity analysis for the uniform versus normal distribution, conducted by Lutz, Sanderson, and Scherbov (1996), showed only insignificant differences in the resulting distribution because of two compensating factors. A uniform distribution (e.g., between an assumed high TFR of 2.1 and a low of 1.3 in Western Europe) results in a lower concentration around the central value (1.7) than in the case of a normal distribution. On the other hand, a certain percentage of cases in a normal distribution lies outside the high and low values, which is not the case with the rectangular uniform distribution. In addition to this numerical near-irrelevance, experts virtually never want to be nailed down to a 100 percent probability range; a normal distribution with some low probability tails seems to be the more natural choice. The other question of what difference it makes to have somewhat different proportions of the total distribution between the high and low values has been simulated by Lutz and Scherbov (1997; 1998a) in the con text of the Austrian probabilistic population projections. Assuming the high low ranges of the official Austrian population projections alternatively to cover 85 percent, 90 percent, and 95 percent of the uncertainty distributions, the resulting distributions of total population size and old-age de pendency ratios were compared. As expected, both the standard deviations and the differences between the 0.2 and 0.8 fractiles are greatest in the case of the 85 percent assumption, and lowest for the 95 percent assumption, with 90 percent in an intermediate position. It is interesting, however, that the difference between the 85 percent case and the 90 percent case is generally much larger than that between the 90 percent and 95 percent case. This holds with respect to standard deviations and fractiles for total population size and for the old-age dependency ratio. The reason for this is that in the case of 85 percent, not only are more cases outside the given high-low range, but also the tails of the normal distribution are disproportionally longer. As a result the differences between the 90 per cent and 95 percent assumptions are insignificant by any standard. Formal t-tests on the null-hypothesis of equal variances show that this hypothesis cannot be rejected at any period. This is even true for the difference between the 90 percent and the 85 percent case.

In conclusion, the experts need not be nailed down to specifying exactly 90 percent, which may imply false precision. Instead notions such as “roughly 90 percent” or even “approximately 90-95 percent” may be more appropriate as a better reflection of fuzzy human intuition.

Not underestimating the variance

Lee (1999) discusses our use of piecewise linear paths for fertility, mortality, and migration. It is important not to confuse the technical details of our projections with the concept of using expert opinion in making assessments of uncertainty. Our application is only one way of incorporating ranges given by experts. Another is to use an autoregressive approach. The piecewise linear approach uses information about the variances of demographic parameters at two points in time. Alternatively, we could write the equation of the variable of interest as:

$$v_t = \alpha \cdot v_{t-1} + \varepsilon_t,$$

where v_t is the value of the demographic variable at time t, a is a positive parameter greater than zero and less than unity, and ε_t is an independently normally distributed random variable with mean zero and variance σ^2. With exactly the same data used in the piecewise linear approach we can estimate α and σ^2. If we did this instead of using the piecewise linear approach, we would get almost the same results with respect to population size and age structure.

The question about the relationship between the variance in population sizes in the random line and the corresponding autoregressive approach has only been partially addressed. In an analytic paper, Bauer et al. (1999) compare a random line approach, which is not piecewise linear, and a corresponding autoregressive model. They address the question first in the univariate case (no age structure) and then in the multivariate case with the simplification of only one fertile age group. For both cases the authors prove that beyond a certain point early in the process, the variance corresponding to the random line approach is greater than the variance corresponding to the autoregressive approach. The lower variance in the first period results from the assumption for this specific random line model of a strictly linear trend, which implies a very narrow range during the first projection years. In the empirical applications described above, a piecewise linear trend has been assumed that rapidly opens up the uncertainty range over the first five years ("sausage model"). This compensates for the low initial variance in the random line approach.

A simulation exercise carried out by Lutz and Scherbov (1997; 1998a) is based on 1,000 runs of the corresponding autoregressive and random line models using the Austrian data (full Leslie matrix with all reproductive age groups). They find that again, after an initial period, the dispersion (as measured by fractiles) of the autoregressive model is lower than that of the random line model. In the medium run and for simulations up to 2050, the standard deviations are also lower for the autoregressive model, for both population size and the dependency ratio.[3]

Based on the analytic proof and the simulation exercise described here, it is safe to say that the probabilistic approach relying on linear trends in the components does not systematically underestimate the variance of the output parameters in the medium to long term relative to the autoregressive model.

Expert opinion about uncertainty can be incorporated into the model in various ways. A piecewise linear approach is one and the autoregressive approach is another. The use of expert opinion does not mandate either method.

Implementation

When a change in a long-established tradition of population projections is recommended, the burden of proof lies with those suggesting the reform. The proposed new practice must have clear advantages over the accepted practice; it should be consistent with the tradition of thinking in the institution concerned and the procedures by which projections have been defined in the past; and it should not cost too much. In the best case for the institution, the new practice should add a useful and inexpensive element to population projections without forcing the institution to discontinue any earlier activities, restructure their administrative processes of defining official projections, or produce something that may confuse the users by telling a different story than the conventional projections.

Although this sounds like an impossible combination of conditions, the expert-based probabilistic approach discussed in this chapter may actually meet all these criteria. The advantages of the probabilistic approach over a conventional approach have been discussed and need not be repeated here. A harder condition to meet is that of institutional and intellectual continuity. In the past, official statistical agencies have resisted proposals for time series-based probabilistic projections because of the resulting structural discontinuity. Changing approaches would introduce inconsistency and competition with their traditional

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[3] In the very long run (beyond 2050) this still holds for population size, while for the dependency ratio the standard deviations of the two models start to converge again.

projections, since the two approaches would have been independent and have given different results. Very few users would have been able to differentiate the approaches and appreciate the additional information; the rest would most likely be confused. This may seem too high an expense to an institution.

The expert-based approach is much more agreeable to statistical agencies in this respect. It is an expansion of the traditional approach, adding to it without forcing any discontinuation. In the case of the application to Austria, the probabilistic projections are based on exactly the same assumptions as have been defined for the official Austrian projections by a long established procedure of advisory committees. These committees, which have already defined high, central, and low assumptions for the three components, could readily be taken as the expert groups with the only remaining assumptions ref erring to the proportion of all cases covered by the high-low range. Hence, there is no inconsistency between the two projections, and the official medium variant becomes the median projection of the probabilistic set. All other official variants are then embedded into the full probabilistic range. The statistical office can continue to publish those variants as before, but, in addition, can tell interested users the probabilities that the real trend will lie above or below the given figures.

As to the costs, the increasing speed of micro-computers makes even a very large set of cohort-component projections an easily manageable task. The main challenges are with respect to data management, but it should not be too difficult to produce a user-friendly piece of software that can be distributed free of charge to all agencies interested in making probabilistic projections along the lines of this approach. All that is needed is a starting population and assumed uncertainty distributions about the future course of fertility, mortality, and migration rates. And even in this respect the software can be designed to assist the experts in their decisionmaking and to demonstrate the consequences of alternative assumptions.

One criticism of probabilistic population projections is that they con fuse the user by not providing one variant that can be used unambiguously. But is it defensible to give the user only one set of fertility, mortality, and migration trajectories, when there is an infinite number of possible trajectories of population change? The chance that any particular trajectory will occur is zero. However, there is always a non-zero chance that it will fall into a certain range. By using a probabilistic approach we can estimate this chance. If the user of a projection wants only one variant, he can still use mean or median values for the projected population. At least both have statistical interpretations and are the result of calculations based on a range of simulated trajectories.

Finally, the expert-based approach to probabilistic population projections can reduce the confusion of users faced with competing population projections. In Germany, for instance, where at least ten sets of population projections have been issued by different institutions and individuals (many of them with several variants), a parliamentary committee on demographic change has recently commissioned probabilistic projections to produce one synthesis of the certainties and uncertainties of future population trends in Germany (Lutz & Scherbov 1998b). This approach not only provides more information, but also renders it unnecessary to make the difficult, if not impossible, choice (because of the mix of substantive and institutional criteria) of one projection while rejecting all the others. Instead, each projection with all its variants can be given a proper place in one joint distribution that is informed by expert knowledge from all institutions and individuals who work in the field. This framework also allows the incorporation of nonconformist views that would usually be disregarded. Of course, the final responsibility for the shape of the assumed uncertainty distribution remains with the producers of the projection. There is no way around personal responsibility for expert choices made in any population projection.

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Conditional Probabilistic Population Forecasting[1]

Warren C. Sanderson, Sergei Scherbov, Brian C. O'Neill and Wolfgang Lutz

1 Introduction

The last decade and a half has witnessed rapid development in the area of probabilistic population forecasting (see Alho 1990; Alho 1997; Alho & Spencer 1985; Keilman et al. 2002; Lee 1999; Lee & Tuljapurkar 1994; Lutz et al. 1996; Lutz et al. 1997; Lutz et al. 2001; Lutz & Scherbov 1998; Lutz & Scherbov 2002; and Pflaumer 1988, among others). A probabilistic forecast goes beyond a traditional deterministic one by providing an integrated estimate of the forecast's uncertainty, often a crucial quantity for decision-makers. These forecasts give distributions of outcomes rather than single numbers resulting from alternative scenarios. Since policy-makers often prefer to think in terms of alternative scenarios (for example, outcomes with and without a certain policy), the question has arisen as to whether it is possible to make conditional forecasts in a probabilistic context.

This paper answers that question by demonstrating how to obtain conditional probabilistic population forecasts. We do this with two different kinds of examples. The first is the probabilistic analog of deterministic scenarios and the second is a new category that we call "future jump-off date forecasts". Both are important for policy analysis.

Scenario analysis is essential for policy-makers because it allows them to answer "what if" type questions. For example, they may want to know what the age structure of their country would be in fifty years if fertility were lower than in the official projections. Future jump-off date forecasts are valuable because they help in answering questions about the value of waiting to learn about how the future is unfolding. For example, a country may be deciding on whether to build up a retirement fund for its citizens. The decision could be made to raise taxes now or to wait ten years to improve its projections of future population aging. Future jump-off date forecasts allow us to assess how much uncertainty about the future is likely to be resolved by waiting.

In Section 2, we briefly discuss the probabilistic forecasting methodology used in Lutz et al. (2001). It is the basis for the quantitative examples in the next two sections. In Section 3, we discuss the probabilistic counterpart of traditional scenario analysis. Section 4 presents a first look at future jump-off date forecasts. Section 5 contains some concluding thoughts.

2 An Introduction to the Methodology

Creating population forecasts from an initial distribution of the population by age and sex and forecasts of total fertility rates (TFRs), life expectancies at birth, and net migration rates is a widely accepted procedure. Probabilistic population forecasts differ from deterministic forecasts in that they quantify the uncertainty of the course of future rates and therefore must specify future total fertility rates, life expectancies, and net migration rates as distributions and not as points. Distributions can also be used to quantify other uncertainties such as those relating to the base population size.

In order to generate the required distributions, Lutz et al. (2001) let v be the total fertility rate, the change in life expectancy at birth, or net migration to be forecasted for periods 1 through T and v_t be its forecasted value at time t. The forecasted value, v_t, can

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be expressed as the sum of two terms, its trend (mean) at time t, $\overline{v_t}$, and its deviation from the mean at time t, ε_t. In other words, $v_t = \overline{v_t} + \varepsilon_t$, where ε_t is the idiosyncratic noise. The $\overline{v_t}$ were chosen based on the arguments given in Lutz et al. (1994; 1996) and updated based on subsequent information. The ε_t term is assumed to be a normally distributed random variable with mean zero and standard deviation $\sigma(\varepsilon_t)$. The $\sigma(\varepsilon_t)$ are also based on arguments from the same sources.

Due to the persistence of the factors represented by the ε_t, we would generally expect them to be autocorrelated. One of the most commonly used methods of specifying how the ε_t term evolves over time is the simple autoregressive formation (AR(1)), where $\varepsilon_t = \alpha \cdot \varepsilon_{t-1} + u_t$, where u_t is an independently distributed normal random variable with mean zero and standard deviation $\sigma(u)$. Another commonly used method is the moving average formation of order q, MA(q) where q is the number of lagged terms in the moving average. We use the following moving average specification:

$$\varepsilon_t = \sum_{i=0}^{q} \alpha_i \cdot u_{t-i}$$

where u_{t-i} are independently distributed standard normal random variables. To ensure that the standard deviation of ε_t is equal to its prespecified value,

$$\alpha_i = \frac{\sigma(\varepsilon_t)}{\sqrt{q+1}}$$

The choice between AR(1) and MA(q) does not have to do with estimation, but rather with representation. Data do not exist that would allow the estimation of the parameters of either specification at the regional level used in Lutz et al. (2001). Neither is more theoretically correct than the other. Both are just approximations to a far more complex reality. When comparably parameterized, they produce very similar distributions of ε_t.

The choice between the two, therefore, rests on which more accurately reflects arguments concerning the future. From our perspective, the moving average approach has the advantage that the $\sigma(\varepsilon_t)$ terms appear explicitly making it easier to translate ideas about the future into that specification.

The future levels of vital rates can be correlated in different ways. Most important are (a) the correlations between deviations from assumed average trends in fertility and mortality rates, (b) the autocorrelation of deviations within each series of vital rates and (c) the correlations among the deviations from the average vital rate trends in different world regions. The forecasts of the world's population used in this paper assume: (1) a zero correlation between fertility and mortality deviations from their trends within regions, (2) a 31 term moving average specification separately for fertility and mortality deviations, which implies an autocorrelation between deviations one year apart of around 0.96, and (3) cross-regional correlations of fertility and mortality deviations within each year of 0.7 and 0.9 respectively. This methodology is considerably different from the one used in Lutz et al. (1996; 1997), where piecewise linear paths for future vital rates were used.

Due to temporal and regional correlations, vital rates paths for all regions are determined simultaneously and then used to make population forecasts, which were aggregated to the world total. This process was repeated 2,000 times, generating a distribution of world population sizes for each year from 2001 to 2100.

3 Conditional Probabilistic Forecasting and Scenario Analysis

One important audience for probabilistic forecasts is the user community. Often when demographers want to communicate the importance of particular variables in their forecasts to members of this community, they use scenarios. In population forecasting, scenarios are typically clear "if … then" statements in which the implications of a certain set of assumptions on fertility, mortality and migration are being demonstrated (Lutz 1995). Such scenarios can illustrate the laws of population dynamics but do not give the user any information about the likelihood of the described path. For instance, an immediate replacement fertility scenario merely shows what would happen if fertility immediately jumped to the replacement level without saying that this is a likely or even plausible path. For policy makers who want to know what would be the long-term consequences of alternative fertility trends resulting from alternative policies, for example, such scenarios can nonetheless be useful guides. Conditional probabilistic forecasting is a way of posing and answering the same type of question within a probabilistic framework.

The first discussion of conditional probabilistic population forecasts, of which we are aware, appears in Alho (1997). Alho first turned the deterministic world population forecasts in Lutz et al. (1994) into a probabilistic one and computed the probability of the world's population falling between the high and low scenarios. Next, Alho considered the case where the UN's world population forecasts for 2025 could be regarded as a Lutz et al. (1994) forecast conditional on the success of family planning programs. Alho showed that if the probability of being between the UN's high and low variants was 75 percent, then those programs would have to reduce the variance of the probabilistic version of the Lutz et al. (1994) forecasts by at least 42 percent. Alho regards this as "much too high to be credible" in light "of the past record of ineffectiveness of government interventions concerning fertility in the industrialized countries" (p. 83). He showed that if the reduction in the variance were less than 42 percent, then the probability content of the interval between the UN high and low variants must be less than 75 percent.

Alho (1997) is an example of taking known unconditional and conditional distributions and learning about the nature of the conditional distribution by studying the plausibility of the conditions needed to obtain it from the unconditional one. Here, an example that is at the other end of the continuum, is presented. Starting with unconditional distributions and conditions that are of interest to policy-makers, the example demonstrates how probabilistic forecasting can produce conditional distributions that are useful in scenario analysis. There are many possible intermediate cases as well, where information about some aspects of conditional distributions and some features of the conditions themselves are combined in order to investigate particular questions. An example of this can be found in O'Neill in this issue (O'Neill 2004).

The approach used here was developed in Sanderson et al. (2004). An application on whether immigration can compensate for Europe's low fertility appears in Lutz & Scherbov (2002). The example begins with Figure 1, which shows the distribution of the world's population in 2050 conditional on average fertility and mortality levels for the world over the period 2000-2050. The x-axis is divided into three ranges labeled "low fertility", "medium fertility" and "high fertility". Low fertility includes all of the 2,000 simulated futures where the average total fertility rate in 2000-2050 was below 1.6. Medium fertility includes those paths where the average total fertility rate was between 1.6 and 1.8; and high fertility includes paths in which the average total fertility rate (over the whole projection period) was above 1.8.

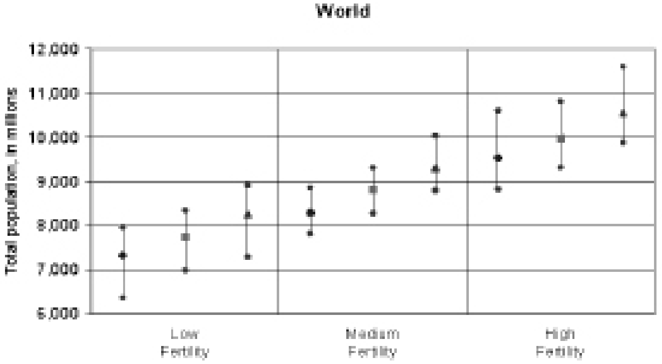

Figure 1. Median and interdecile ranges for the world population, conditional on three alternative fertility and mortality levels. The three lines within each category refer to the low (left), central (middle) and high (right) groups of life expectancy. Source: Authors' calculations.

Within each of the three panels there are three lines that have different symbols near their centers. The lines with the diamonds near their centers refer to paths where the global average life expectancy at birth was lower than 68 years. The lines with the dented squares refer to paths where the average life expectancy was between 68 and 71 and the lines with triangle shapes to paths with average life expectancies over 71. The aggregations of the total fertility rates and life expectancies at birth were chosen so that one-third of our paths was in each group. The symbols are placed at the medians of the distributions. The circles at the endpoints of the lines indicate the 80 percent prediction intervals. Now we are in the position to answer some "what-if"-type questions. For example, what would be the effect on world population size in 2050 of high fertility trends versus low fertility trends over the coming decades combined with the medium range of uncertainty for future mortality? We can immediately read the answer off the figure. In the middle group, the median population of the world in 2050, if we experienced low fertility, would be around 7.7 billion people with the 80 percent prediction interval covering the range 7.0 to 8.3 billion people. If we experienced a high fertility world, the median population would be considerably higher, around 10.0 billion people, with a prediction interval between 9.2 and 10.9 billion people. The difference between the medians is 2.3 billion people, which is quite large considering that the median of the unconditional population distribution is 8.8 billion people. Clearly, the difference in fertility is very significant.

We can also read the figure to tell us about the influence of differences in life expectancies on future population size. We can do this easily by looking at the middle panel, labeled "medium fertility". When life expectancies are in the low group, the median population size is 8.3 billion. When they are in the high group, the median population is 9.2 billion. Therefore, in 2050 the effect on population size of moving from low to high fertility, keeping life expectancy constant, is much larger than the effect of moving from low to high life expectancy, keeping fertility constant.

Figure 2 is similar to Figure 1, except that it deals with the proportion 60 years and above. As fertility increases, the proportion 60 and above decreases, but as life expectancy increases, the proportion gets larger. Let us consider the difference in the proportion due to having high fertility as opposed to low fertility, again assuming medium life expectancy.

The median proportion is 25 percent when fertility is low and around 19 percent when it is high. Assuming medium fertility and varying mortality, we see that when mortality is low the proportion is below 20 percent, compared to 24 percent when mortality is high. Thus, the effects of fertility and mortality are more similar in determining the proportion 60 and above than they are in determining population size.

The two examples in this section show that in making the transition from deterministic to probabilistic forecasting, we do not have to give up on answering the kinds of “what-if” questions that users and policy-makers so often pose.

4 Conditional Probabilistic Forecasts with Future Jump-Off Dates

In many policy areas, we come across the question: Should we act now or should we wait until we learn more? Waiting has a cost because it can foreclose certain policy options or make them more expensive. On the other hand, by waiting policy-makers could possibly acquire important and relevant information, and avoid potentially unnecessary policy interventions. Since population is an important driver of many processes, it is valuable to know how much the demographic outlook might change if we wait.

For example, the question of whether to act now or wait to learn more is central to the debate over climate change policy. The climate change issue is characterized by both long timescales – today’s emissions of greenhouse gases will affect the climate for decades to centuries – and substantial uncertainties in climate impacts on society and costs of emissions reductions. Many argue that it would be beneficial to wait to learn more (and reduce uncertainties) before deciding whether, and how much, to reduce emissions. This strategy would avoid investments in emissions reductions that may turn out to be unnecessary. Others argue that reductions should begin now, because if climate change turns out to be serious, we would later regret not acting early. The question of how the potential for learning about various aspects of the problem affects today’s optimal decision remains unresolved (Webster 2002). It is possible that learning about the outlook for future population growth could impact such decisions. Population is one factor affecting the outlook for future greenhouse gas emissions. If, by waiting a decade or two, we learn that population is likely to be much lower in the future than we currently expect, our outlook

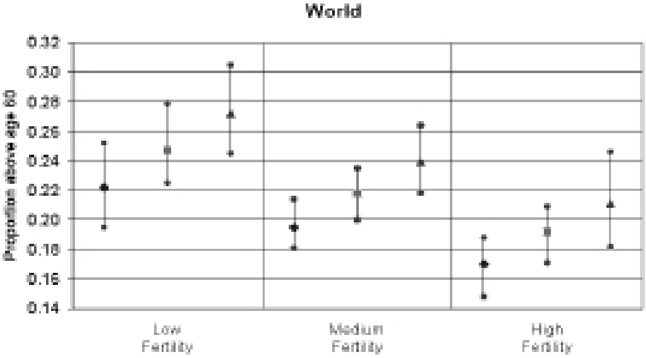

Figure 2. Median and interdecile ranges for the global proportion above age 60, conditional on three alternative fertility and mortality levels. The three lines within each category refer to the low (left), central (middle) and high (right) groups of life expectancy. Source: Authors’ calculations.

for future emissions will also likely be revised downward, reducing the urgency of emissions reductions. If we learn that population is likely to be much higher, our outlook for emissions will also be higher, justifying more aggressive action to reduce emissions.

Probabilistic forecasts with future jump-off dates are constructed to help us learn about the value of waiting for more information. These forecasts are, of course, conditional on what happens between the beginning of the current forecast period and the future jump-off date. For example, imagine that it is the year 2000 and forecasts are made of the distribution of the size of the world's population in 2050. How different would the forecasted distribution of population sizes be in 2050 if the forecast were made in 2010 instead of 2000? We do not have to wait to 2010 to answer this question. The technique of making probabilistic forecasts with future jump-off dates allows us to think about this question now.

Projections in 2010 may differ from projections in 2000 because something is learned between now and then. At a minimum, the values of demographic variables like population size, fertility, mortality, and migration in that ten-year period will be observed. Other factors such as new policies, economic trends, or social conditions that are relevant to the outlook for future demographic rates will also be observed. It is possible as well that demographic theory will be improved through research, that new breakthroughs in health (or new epidemics of disease) will occur, or that new contraceptive technology will be developed. All of these types of learning could change the outlook for the future. Learning based on these other factors is not considered here. In the example below, learning is only based on the observation of demographic variables. While learning by observation is only one type of learning, it is likely to be an important one in population projections.

In this section, we take some small first steps toward understanding how this passive learning process takes place, so that users of forecasts are not surprised when forecasts change and so that policy makers can use probabilistic forecasts in the design of adaptive policies.

Let us imagine that it is now 2010 and all the relevant population information has been compiled and is available. Certainly it would be appropriate to make new forecasts, even if the methodology and assumptions that were originally used were completely correct. The forecasts based in 2010 would take into account what actually happened between 2000 and 2010. Without actually making new forecasts, the projections made in 2000 could be used to anticipate what new projections would look like.

In order to make this inquiry practical, a very simple approach will be used here. Instead of observing exact population characteristics, the assumption is made that only whether or not global population size is above or below the median of its distribution can be observed. There is nothing theoretically attractive in dividing the observations into only two groups in 2010, but it makes this introduction to passive demographic learning as simple as possible.

Table 1 consists of two panels. Panel A provides the distributions of future world population size expressed in intervals below 6 billion, 6 to 7 billion, 7 to 8 billion, and so on with the uppermost interval being above 12 billion. The numbers in the cells are the percentages of our 2,000 simulated future population paths. Median population sizes are in column 9. The tenth column contains an uncertainty measure, the relative interdecile range (RIDR) defined as the difference between the ninth decile and the first decile of the distribution divided by the median.

Panel B is based on a division of the 2010 distribution into population paths that were above the median in that year and those that were below it. There are 1,000 observations in each of these subgroups. There are two rows in Panel B for each decade following 2010, one labeled with an "L" and another with an "H". The "L" rows are the population distributions at the indicated date for the observations that were below the median in 2010 and the "H" rows are from the paths that were above the median in 2010.

One disadvantage of this very simplified example is that the forecasts with jump-off dates in 2000 and 2010 are not exactly comparable. The vital rate paths used in the 2000 forecasts all start at their observed values, while the paths in forecasts that have the 2010 jump-off date have a distribution of starting values. One way of testing the plausibility of this example is to consider the uncertainty of forecasts of various durations based on a jump-off date of 2000 and a jump-off date of 2010. Holding duration constant, the example would be questionable if the uncertainties of N year ahead forecasts were very different depending on whether they were made in 2000 or 2010. When the jump-off date is the year 2000 and a forecast is made for 10 years into the future, the uncertainty measure in 2010 is 0.062, which can be read off the row in Panel A labeled 2010. In the case of a forecast made 10 years ahead based on being below the median in 2010, the uncertainty measure in 2020 is 0.088. This can be read off the row in Panel B labeled 2020/L.

The uncertainty measures for 10- through 90-year ahead forecasts based on 2000 and the two sub-samples from 2010 are shown in Figure 3. The results from the two 2010 groups track those from 2000 quite well, but are always slightly higher than the uncertainty measures based on 2000. Figure 3 is what is expected given the construction of the example and it suggests that it is plausible to proceed.

The median population forecast for 2100 based on information up to 2000 is 8.414 billion people. After a 10 year wait, the median forecast for 2100, based on being above or below the median in 2010, would either be 7.652 billion or 9.328 billion. It would seem that if anyone were to predict 914 million more people in the world in 2100 from the perspective of 2010, the forecaster must have made a big mistake in 2000. Yet, this could well happen even if the methodology is probabilistically correct. A prediction of a 2100 population size in 2010 that is 762 million smaller than the one that was predicted in 2000 is also easily possible. These are substantial differences. Clearly, forecasts of the future will be different in 2010 than they are today. One interesting feature of probabilistic forecasting is that it can give us some idea about how much different future forecasts could be from current ones, and with what likelihood.

Population size in 2010 has such a persistent effect because of a number of factors. First, past population size influences future population size. Paths that yield large populations in 2010 will also yield large populations in 2100, even if population growth rates after 2010 are the same. Second, some populations are large in 2010 because they had high fertility rates. These high fertility rates alter the age structure of the population making it younger. Younger populations tend to grow more, other things being equal, a process that demographers call "population momentum". Fertility and mortality themselves have persistence built into them. The persistence of fertility and mortality means that on paths where fertility was high and mortality was low, leading to relatively large populations in 2010, they are likely to remain high and low respectively for a while. The effects of the persistence of fertility and mortality over time are compounded by the relatively high interregional correlations of fertility and mortality, by the persistence caused by population momentum and by the size effect itself.

Table 1. Forecasted distributions of the world's population size beginning in 2000 and beginning in 2010.

World	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: 2000 Jump-Off Date										
	Below 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	Above 12	Median	RIDR*
2000	0	100	0	0	0	0	0	0	6055	0
2010	0	85.05	14.95	0	0	0	0	0	6828	0.062
2020	0	8.05	81.45	10.5	0	0	0	0	7538	0.129
2030	0.1	3.05	41.85	47.35	7.5	0.15	0	0	8085	0.195
2040	0.15	3.75	24.85	40.25	25.15	5.2	0.65	0	8525	0.27
2050	0.5	5.05	18.95	30.95	26.8	13.45	3.3	1	8796	0.352
2060	1.55	7	17.45	25.75	22.35	16.25	6.45	3.2	8935	0.427
2070	4	8.35	16.9	21.2	19.9	15.05	8.5	6.1	8974	0.52
2080	6.8	10.1	16	18.45	18.45	12.55	9	8.65	8890	0.606
2090	10	12.75	14.85	17.9	15	12.25	6.45	10.8	8678	0.702
2100	14.25	14.05	14.45	16.5	12.9	10.45	6.85	10.55	8413	0.779

* Relative Interdecile Range (RIDR) is measured as the difference between the ninth decile and the first decile divided by the median.

World	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel B: 2010 Jump-Off Date										
	Below 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	Above 12	Median	RIDR**
2020/L	0	16.1	83.9	0	0	0	0	0	7268	0.088
2020/H	0	0	79	21	0	0	0	0	7787	0.081
2030/L	0.2	6.1	70.3	23.4	0	0	0	0	7704	0.147
2030/H	0	0	13.4	71.3	15	0.3	0	0	8486	0.139
2040/L	0.3	7.5	42.3	42.4	7.4	0.1	0	0	7996	0.224
2040/H	0	0	7.4	38.1	42.9	10.3	1.3	0	9083	0.216
2050/L	1	9.9	31.1	36.6	17.9	3.2	0.3	0	8152	0.294
2050/H	0	0.2	6.8	25.3	35.7	23.7	6.3	2	9521	0.279
2060/L	3.1	12.8	26.9	31.3	17.3	6.8	1.6	0.2	8256	0.389
2060/H	0	1.2	8	20.2	27.4	25.7	11.3	6.2	9760	0.352
2070/L	7.8	13.6	23.9	25.2	17.4	8.7	1.9	1.5	8213	0.485
2070/H	0.2	3.1	9.9	17.2	22.4	21.4	15.1	10.7	9891	0.438
2080/L	12.5	14.7	22.2	19.8	16.9	7.9	4.1	1.9	8045	0.568
2080/H	1.1	5.5	9.8	17.1	20	17.2	13.9	15.4	9816	0.536
2090/L	16.1	18	18.5	18.3	13.3	9.4	3.6	2.8	7888	0.641
2090/H	3.9	7.5	11.2	17.5	16.7	15.1	9.3	18.8	9638	0.647
2100/L	22	17.7	16.6	17.6	9.9	9	3.6	3.6	7652	0.716
2100/H	6.5	10.4	12.3	15.4	15.9	11.9	10.1	17.5	9328	0.734

* Relative Interdecile Range (RIDR) is measured as the difference between the ninth decile and the first decile divided by the median.

Source: Authors' calculations.

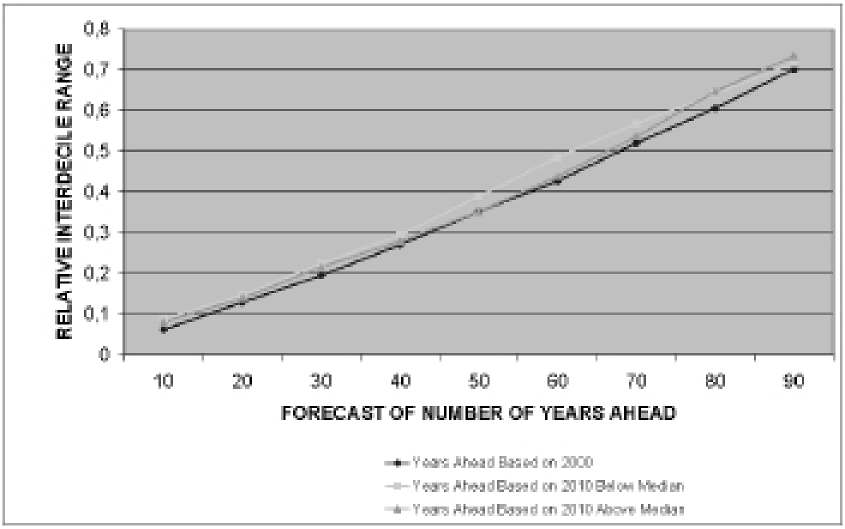

Figure 3. Comparison of the Relative Interdecile Ranges (RIDR) for forecasts made for 10 through 90 years ahead starting from 2000 and starting from an observation either above the median or below the median in 2010. Source: Authors' calculations.

It is crucially important that attention be given not only to the effects of the passage of time on the median forecast, but to the entire distribution of forecasted population sizes. Most of the differences in the distributions based on the paths above and below the median in 2010 are in the extremes (tails) of the distributions. For example, 6.5 percent of the paths that were above the median in 2010 resulted in populations of less than 6 billion in 2100, compared to 22.0 percent of the paths that were below the median in 2010. The difference at the high end of the distribution is even more striking. Over 17 percent of the paths that were above the median in 2010 ended the century with 12 billion people or more. In contrast only 3.6 percent of the paths that were below the median in 2010 did so.

This has been a very short and simplified presentation of the basic concepts of conditional probabilistic forecasting with future jump-off dates. It is meant only to be suggestive. This analysis of learning with the passage of time has illustrated how sensitive the long-term population outlook is to near-term trends. It can also help to understand why projections of population size in 2100 have changed so significantly over the past 10 years. We have simply learned a great deal over the past decade. During this decade population growth has been lower than originally expected and this has significantly decreased our new long-term expectations.

5 Concluding Thoughts

Conditional probabilistic projections represent a way to combine the benefits of probabilistic projections, particularly the quantification of uncertainty, with the benefits of alternative scenarios, which give clear indications of the sensitivity of results to underlying assumptions. We have shown that the same kinds of conclusions about, for example, the relative importance of fertility and mortality trends to population size outcomes can be drawn using conditional probabilistic forecasts as can be drawn using alternative deterministic scenarios. An added benefit is that the conditional probabilistic forecasts provide an estimate of the likelihood of the underlying demographic conditions, as well as an estimate of their effect on outcomes. These projections can be extremely useful to both the research and policy communities. For instance, many analyses of the potential for long-term environmental change are based on the approach of considering a set of alternative future scenarios conditional on different sets of assumptions about future development. The scenario approach dominates as a response to deep uncertainty about the many socio-economic, technological, and environmental factors that must be included in such analyses. Conditional probabilistic projections present a possible means of retaining some of the advantages of the probabilistic approach without discarding the benefits of conditional scenarios (see O'Neill 2004 for an example).

Probabilistic projections with future jump-off dates, which are conditional on how population characteristics evolve between now and the future jump-off date, present a new way to address an important set of research questions that are also policy relevant. They provide a means of anticipating how our forecasts might change in the future and how likely those changes appear to be at the moment. These kinds of analyses cannot be done deterministically. As there can be costs and benefits to changes in the outlook for the future, these projections could have interesting new applications. For example in the climate change issue, the prospects of learning about technological costs, or about physical aspects of the climate system, have been incorporated into analyses of whether it is better to act now or to wait to learn more. However as far as we are aware, no such analysis – for climate change or any other issue – has been performed taking into account the prospects for learning about the outlook for population.

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Probabilistic Population Projections for India with Explicit Consideration of the Education-Fertility Link[1]

Wolfgang Lutz and Sergei Scherbov

1 Background

Asia's population, which comprises more than half of the world's population, is currently going through significant structural changes. While the population of Asia is still expected to grow from currently 3.5 billion to around 4.8 billion in 2050, for the second half of the century we expect the beginning of a population decline (see Lutz et al. 2003). Simultaneously, it will experience significant population aging. Asia is also in the midst of a major structural transition with respect to its human capital, i.e., the number of people by level of education. While the great majority of older cohorts of Asians have little to no education, the younger cohorts tend to be much better educated.

Since the better-educated women have lower fertility, this has direct demographic consequences. The improvements have been particularly impressive in China, where it is estimated that within two decades China will have more working age people with secondary and tertiary education than Europe and North America taken together (Lurz & Goujon 2001).

But trends in Asia are very heterogeneous. China, which is currently the world's most populous country, has fertility well below the replacement level and is soon expected to be surpassed in size by India, which has higher fertility and a much younger population. For most of the 21st century, India will be the world's most populous country, with a projected 17 percent of the world's population in 2050. Hence, the future of the world's population will be significantly influenced by the future trends in India's population.

These future demographic trends in India are, however, highly uncertain. A lot will depend on the still unknown speed of fertility decline and the post-transition fertility level as well as the future spread of the AIDS epidemic or other health problems. The projections cited above only refer to the best guess from today's perspective, or more precisely the median of an uncertainty distribution. It is hard to say precisely how social, economic and even environmental changes will play together in determining the future trends in fertility, mortality and migration in India. On the other hand, we are not completely ignorant about the future size or structure of the population. Many of the people who will be alive in 2030 have already been born and we know their cohort sizes. Also, we can assume with high probability that a country in the midst of its fertility transition will continue with its fertility decline until a low level is reached. How should we communicate this to policy makers, who want to get the best synthesis of what we can say about the future trends to base their planning on these forecasts? To tell them that we simply do not know will not serve them well, especially if we think we know more than nothing. It is a bit more informative to say, here is one scenario and here is another, but we do not know how likely they are. This still does not help them much in their planning. Giving them just one projection, however, and telling them that this is the way the future will look, is probably highly welcomed by the planners but dangerous, if there are any costs associated with a projection error. A false feeling of certainty can be harmful and we should not create it, especially when we know

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better. Hence, the challenge for the population forecaster is to try to be specific of what we think is more certain and what is less certain, and to what degree uncertainties differ. The most comprehensive and efficient way to do so is to produce probabilistic forecasts.

In the context of developing countries with very limited data availability, methods of probabilistic population projections that are based on time series analysis are often not applicable because there are no time series. Also, methods that are based on the ex post error analysis of past population projections are of very limited applicability in a country that is in the midst of a demographic transition. Because of this one still expects significant structural change-we know that the future will be different from the demographic changes that occurred over the past decades. This essentially leaves us with the third approach to probabilistic forecasting, which is based on the evaluation of expert arguments. The strengths and weaknesses of expert-based approaches are extensively discussed elsewhere (Lutz et al. 1999; Lutz et al. 2004). In short, the key to avoid most personal biases in assessing the uncertainty ranges of future demographic trends is to focus on the evaluation of substantive arguments that experts put on the table and hence try to inform the subjective probability distribution by as much objective and scientific information as possible.

In the Asian context this task was taken on by the Asian MetaCentre for Population and Sustainable Development Analysis. The Asian MetaCentre is a group of population research institutes throughout Asia with headquarters at the National University of Singapore and a training branch at Chulalongkorn University in Bangkok (for more information, see www.populationasia.org). A series of two workshops in 2001 and 2002 was dedicated to an exercise to identify the main drivers of demographic change in Asia and to translate these insights into probabilistic projections. This included the more traditional analysis of past time series when available, the study of the errors of past projections - where such could be found - and individual expert statements about the assumptions of the most likely trends in vital rates together with subjective quantitative assessments of the uncertainty ranges. This exercise also included new methods, such as a rather large number of in-depth interviews of experts in which they were extensively asked about their reasons for making certain assumptions rather than others, and during which an attempt was made to assess with which assumptions the experts felt more confident or less confident. These interviews were conducted by an expert in cognitive science, who is an expert on experts, but not on population. Based on these findings the exercise then went one step further to try to explicitly model the one structural determinant that has been singled out as the most important one, namely female education, and make the future fertility uncertainty dependent on future education in the context of probabilistic projections. To our knowledge such a structural approach to probabilistic projections has not been applied before.

This approach of expert argument-based projections distinguishes between resource experts who provide the arguments and meta-experts who guide the process and operationalize the assumptions. In this exercise carried out by the Asian MetaCentre, the authors of this paper served as the metaexperts with more than 50 Asian national population experts serving as resource experts. This is explained in more detail in Lutz & Scherbov (2003). In this paper we only focus on discussing the assumptions and projections for India.

2 Fertility Assumptions

We chose to single out the one structural argument about the determinants of the future course in fertility that would feature most prominently in most of the expert interviews. The choice was not difficult, because in addition to the rather diffuse reference to all kinds of

Table 1. Education-specific differentials and total TFR for women in India and China.

	India 2000	China 2000
No education	3.78	2.43
Some primary education	2.89	2.14
Some secondary education	2.36	1.63
Some tertiary education	1.96	1.08
Total Fertility Rate	3.30	1.80

government policies, female education clearly stood out as the single most important factor mentioned. Almost all of the national experts from the different countries in Asia involved in the exercise consistently mentioned that they thought that the improving level of female education has been and will be the main driver of fertility decline.

The line of argumentation in these interviews seems clear: The combination of great educational fertility differentials in Asia (more highly-educated women have significantly lower fertility) with the fact that younger women are and will be more educated than older women, greatly contributes to fertility decline. These educational fertility differentials are pervasive all over Asia and in countries with very different overall levels of fertility.

Table 1 gives the recent educational fertility differentials for women in India and China. It shows the total fertility rate (TFR) for four categories of women: those without any formal education and those with some primary, secondary and tertiary education. The precise definition and discussion of these categories and data sources are given in Lutz & Goujon (2001). The table clearly and impressively shows how in these two major countries, higher education is associated with lower fertility. The total TFR gives the fertility of the total population with weights of the different educational groups corresponding to the current educational composition in India and China.

Figure 1 gives the age-, sex- and education-specific population pyramid for India as estimated for the year 2000. The pyramid clearly shows that younger cohorts of women in India are better educated than older ones, although the gender gap is still significant.

When we think about the future of the national-level fertility in India, we must differentiate between two different effects: (a) the change in the educational composition

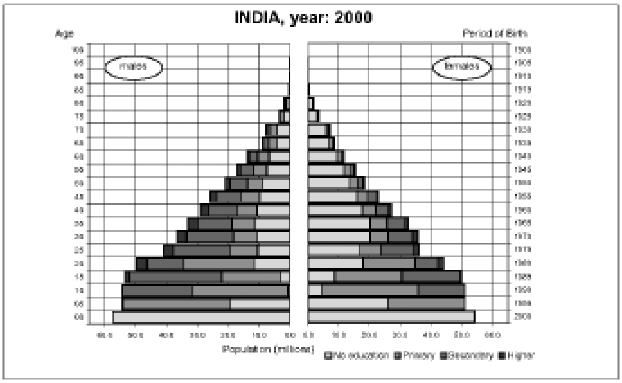

Figure 1. Population pyramid for India, 2000

of the population, and (b) the fertility trends within each educational group. We will first discuss these factors separately and then (c) study their joint effect.

(a) Alternative trends in education

As can be inferred from Figure 1 future improvement in the educational composition of the population is a near certainty. It is already pre-programmed into the age structure. The younger, better-educated cohorts will inevitably become older and replace the older, less-educated cohorts. Disregarding the unlikely case of massive adult education programs only the future education of the young cohorts is uncertain at this point, depending on future school enrolment rates at different levels. Policies can make a difference here. We capture this difference through two alternative and rather extreme scenarios on girls' and boys' education in India, one (pessimistic) scenario in which all enrolment rates stay constant in the future [scenario A: constant enrolment] and another in which India manages to implement the ambitious education goals as defined in the 1994 Cairo World Population Conference (ICPD) [scenario B: ICPD]. This highly optimistic scenario assumes the elimination of the gender gap in primary and secondary education by 2005- 10, 90 percent net primary enrolment by 2010- 15 and secondary enrolment of 75 percent by 2025-30, as well as an increase in transition to tertiary education by 5 percentage points until 2025-30. Trends between 2000 and the target year are based on linear interpolation. The results from these two scenarios are depicted in Figure 2 for the year 2030.

Figure 2 clearly shows that the two scenarios are virtually identical in 2030 for men and women above age 55. For younger cohorts the constant enrolment rates scenario shows an essentially frozen educational composition with a significant gender gap in education being maintained. Under the ICPD scenario the educational composition improves significantly for the younger cohorts and the gender gap essentially disappears below age 25.

(b) Trends in education-specific fertility

During the course of the Asian MetaCentre exercise, there were quite some discussions about what should be assumed in terms of future education-specific fertility trends. We considered three different options for dealing with this issues: (1) assuming proportional fertility changes in all educational categories, (2) assuming convergence of all educational fertility trends to one target level, or (3) assuming that education-specific fertilities will move to the observed levels of another country that is already further advanced in the process of fertility decline. Option (1) is not meaningful as a general rule because in some countries the fertility of university graduates is already so low that no further declines will be expected, despite declines in average fertility. Also, for countries for which time series exist, the declines do not seem to go in parallel. Option (2) is not meaningful in this context, because if we have complete convergence, by definition the changes in the educational composition do not affect aggregate fertility. And substantively all of the Asian countries studied maintained significant differentials, even at very low aggregate fertility levels. For these reasons we chose Option (3), which is consistent with the frequent demographic practice to think in terms of analogies, as is more generally done in the context of the demographic transition. Specifically, for the case of India presented here, we assumed that in 2030, India will have education-specific fertility rates comparable to those of China today.

What is the substantive justification for this particular assumed analogy between China today and India tomorrow? First, the aggregate TFR in India in 2030 is assumed by most projections to go to a level similar to that in China in 2000. Also, India and China are both huge and greatly heterogeneous countries. In this sense the national-level fertility

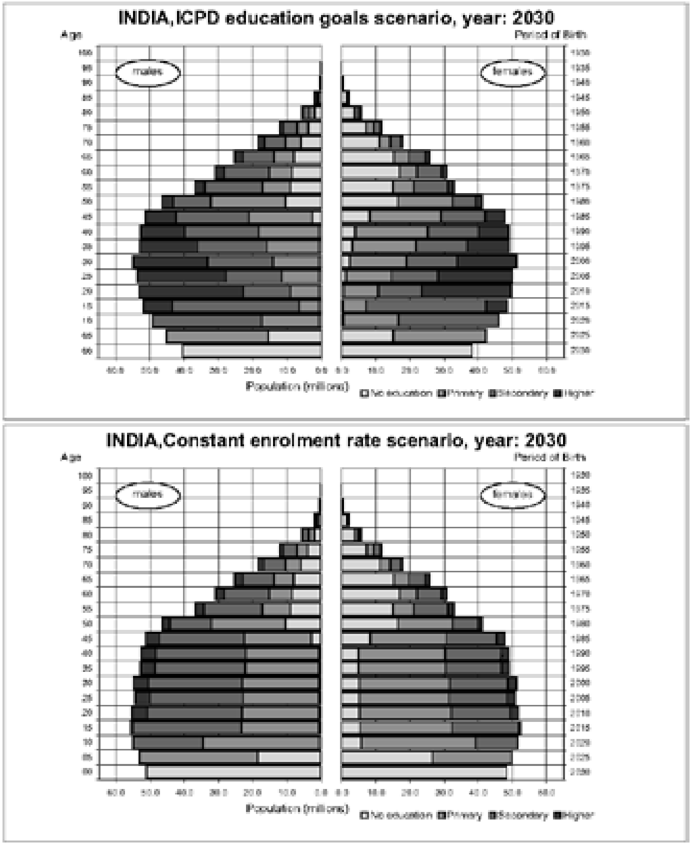

Figure 2. Education-specific age pyramids for India under the two alternative education scenarios in 2030 as described in the text

differentials by education do not just reflect some volatile patterns as they may appear in small populations. Finally, the data given in Table 1 show declines in each educational group of between 26 and 45 percent or on average one-third. A sensitivity analysis that assumes that each of the fertility rates in India in 2000 declines linearly by one-third until 2030 yields virtually the same results as the assumed move to the Chinese pattern of 2000.

(c) Combined scenarios

Table 2 defines 12 scenarios that result from the cross-classification of different future trends in the educational structure of the population, and different trends in education-specific fertility rates. The first four scenarios that keep the educational structure of the population frozen are of a purely hypothetical nature because, as has been mentioned above, it is already embedded in the age structure that the younger, more educated age groups over time will move the age scale and improve the average education of the female population of reproductive age. But it is still important to talk about this hypothetical case of the educational composition by age remaining constant in its current form, because it serves as a point of reference in the minds of experts thinking about this issue. For this reason Figure 3 shows the aggregate level TFR resulting from scenarios 1 and 2 in 2050 as black dots to the right of the figure. If the educational composition remains frozen and the

Table 2. Definition of 12 scenarios combining different possible trends in the educational structure with different assumptions about education-specific fertility trends.

	Educational Structure of Population		
Fertility trends for educational categories	**Structure constant (purely hypothetical)**	**Enrolment rates constant**	**ICPD goals for enrolment**
All fertility rates constant	1	5 (c.enr-c.fert)	9 (ICPD-c.fert)
Rates reach Chinese level by 2030	2	6 (c.enr-medium)	10 (ICPD-medium)
China +0.5 by 2030	3	7 (c.enr-high)	11 (ICPD-high)
China -0.5 by 2030	4	8 (c.enr-low)	12 (ICPD-low)

education-specific fertility remains constant (scenario 1), then clearly the aggregate TFR remains constant over time. Scenario 2 gives the case in which the educational composition remains frozen, but education-specific fertility rates decline as discussed below. In this case the aggregate TFR declines by about one child, which is the fertility trend effect that is completely free of the effect of the changing educational structure.

Figure 3 gives four lines for the cross-classification of the two assumptions for education-specific fertility (constant versus linear change to the Chinese pattern) with the two education assumptions (constant enrolment versus the ICPD scenario). When comparing scenarios 5 and 9 and 6 and 10, respectively, we see that the changing educational structure makes a significant difference, even with identical education-specific fertility trends. By 2050 this difference accounts for more than half a child, i.e., more than one-third of the level of fertility as given by scenario 10. If we also consider the hypothetical case of a frozen education structure (scenario 2), the difference due to differential educational structures becomes almost one child. This clearly illustrates that the experts have made a valid and quantitatively important point when they suggested that the changing educational structure would be a major force towards lower fertility.

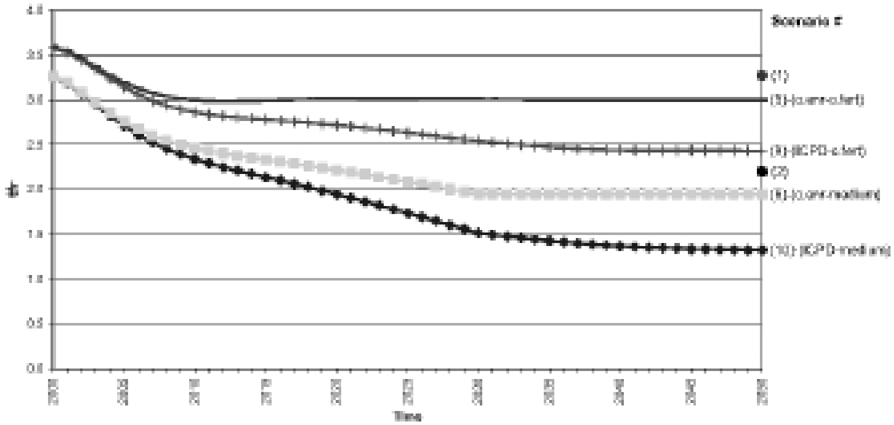

Figure 3. Selected scenarios for combining education assumptions with education-specific fertility trends.

3 Probabilistic Population Projections

How should these insights be translated into probabilistic fertility assumptions? The first thing that is unclear in this context is whether experts, when they stressed the effect of the changing educational composition, had one of the two extremes-the constant enrolment scenario or the ICPD scenario-or something in between in mind. A qualitative discussion with some of the experts at the second seminar indicated that this uncertainty about future school enrolment should be assumed to be part of the total fertility uncertainty. As to the uncertainty of education-specific fertility trends, it was assumed that the uncertainty range considered here would be half a child up and down, as compared to the mean trend (scenarios 6 and 10), which is the linear move from the Indian 2000 rates to the Chinese 2000 rates by 2030. This is consistent with what was assumed in Lutz et al. (2001). There the 80 percent range was assumed to be plus/minus one child if the TFR was above 3.0, and plus/minus 0.5 if it was below 2.0, with linear interpolation in between. Since this was supposed to include the education uncertainty in addition to the education-specific fertility uncertainty, these assumptions are roughly consistent.

Figure 4 gives the four scenarios that combine the plus/minus 0.5 children in education-specific fertility assumptions with the two extreme education scenarios. Following the logic outlined above the appearing range between scenarios 7 and 12 is then taken to represent the 90 percent uncertainty interval of a normal distribution representing India's fertility uncertainty in any given year between 2000 and 2050.

A final step was to translate these fertility uncertainty ranges, which include the education uncertainty in addition to the uncertainty of education-specific fertility trends, into full probabilistic population projections. While the fertility distribution is based on the range between scenarios 7 and 12 as discussed above, the stochastic mortality assumptions are taken from the projections given in Lutz et al. (2001). It is assumed that life expectancy increases by two years per decade with an 80 percent uncertainty range from zero to four years of improvement per decade. For simplicity a closed population is assumed here. The stochastic model chosen assumes annual fluctuations in birth and death rates following the model that is described in Lutz et al. (2004).

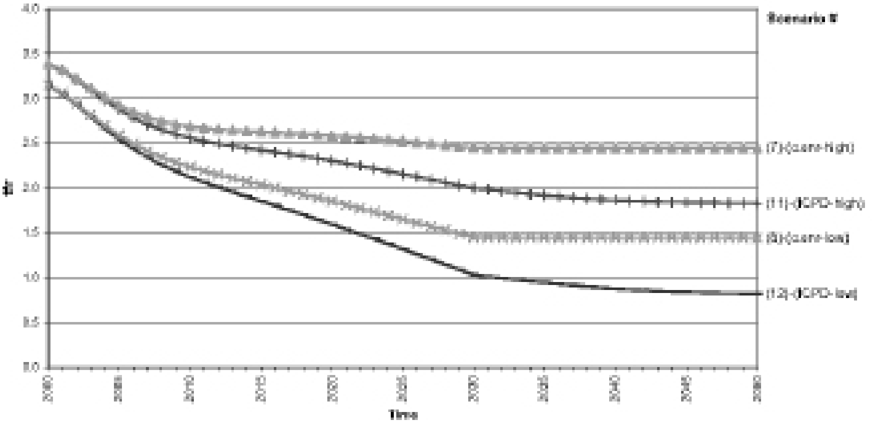

Figure 4. Selected scenarios combining education-specific fertility trends, which are 0.5 children higher and lower than the mean with different future education trends.

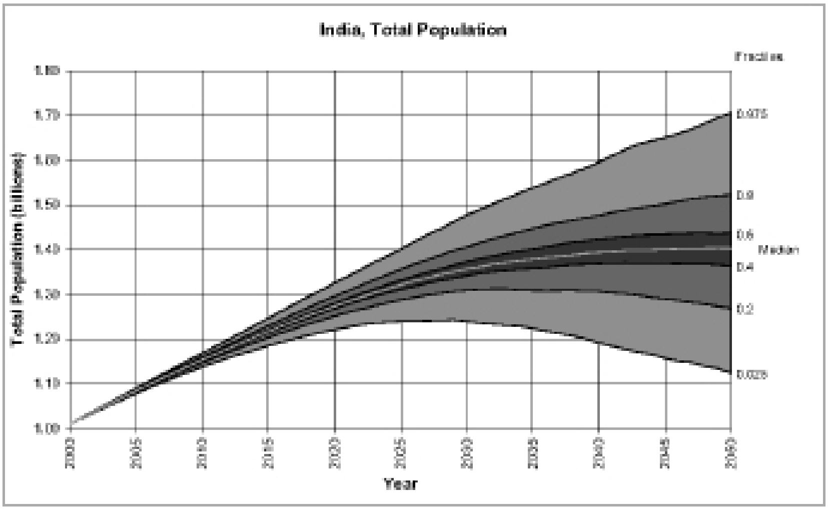

Figure 5. Resulting distribution of total population size in India.

Figure 5 presents the fractiles of the distribution of India's future population size resulting from 1,000 simulations. The white line gives the median of the uncertainty distribution with half of the simulated population futures above that line and half below. The black area shows the inner 20 percent of the uncertainty distribution, the dark gray the inner 60 percent, and the light gray the 95 percent interval. Five percent of the simulated paths lie either above or below the outer lines. As with all such projections the uncertainty range opens up over time. The graph also shows that for the coming two decades the uncertainty range is very narrow, which implies that with very high probability, India's population will increase from presently 1 billion to more than 1.2 billion by 2020. The median shows a stabilization of India's population size after 2035 at a level of roughly 1.4 billion. But the uncertainty range becomes very broad beyond 2030. This is due to the fact that after around 30 years the uncertainty about the number of potential mothers is added to that of the number of births per woman. While in more than 20 percent of the simulations, India's population starts to decline after 2030, in another 20 percent of the cases, it shows very significant continued growth, with the upper end of the 95 percent interval reaching 1.7 billion by 2050.

As discussed above, the future fertility uncertainty is greatly influenced by the uncertainty in the future of education trends. This becomes apparent when comparing the total population numbers in 2050 that result from scenarios 6 and 10 as discussed above, i.e., the central fertility decline assumption combined with the two different educational scenarios. The difference is very significant and in the order of 0.2 billion. In other words, these calculations imply that with otherwise identical assumptions, an India that will follow the ICPD education goals will have 200 million people less than an India with constant school enrolment ratios.

Table 3 gives the numerical results of these new probabilistic population projections for India. The values given refer to the median, with the 80 percent intervals given in parentheses. This shows that despite an expected further population growth of around 40 percent over the coming five decades, India's population will also become significantly older. The proportion above age 65 will increase from currently only 5 percent to around 14percent with the 80 percent uncertainty range going from 0.12 to 0.16. The proportion

Table 3. Medians and 80 percent ranges (in parentheses) for selected projection output parameters in India.

	2000	2025	2050
India, Total Population	1.009 (1.009-1.009)	1.321 (l.268-1.374)	1.403 (l.208-1.603)
India, Proportion below age 15	0.335 (0.335-0.335)	0.238 (0.212-0.260)	0.167 (0.113-0.213)
India, Proportion 15-65	0.615 (0.615-0.615)	0.691 (0.671-0.714)	0.697 (0.660-0.733)
India, Proportion above age 65	0.050 (0.050-0.050)	0.071 (0.068-0.075)	0.138 (0.117-0.161)
India, Old-Age Dependency Ratio (65+ / 15-65)	0.081 (0.081-0.081)	0.103 (0.099-0.107)	0.198 (0.172-0.228)
India, Support Ratio	12.395 (12.395-12.395)	9.690 (9.332-10.053)	5.060 (4.388-5.811)

of children below age 15 will likely decrease to about half its level, from currently 0.35 to only 0.17. For the children, the 80 percent uncertainty interval is much larger, ranging from 0.11 to 0.21.

The fact that the uncertainty ranges differ greatly by age is most clearly shown by the probabilistic age pyramid in Figure 6. Unlike such pyramids for industrialized countries, where there is visible uncertainty at a very old age due to the uncertainty about the path of future old age mortality, this is not yet visible in India because the population is still much younger and life expectancy is still much lower. Hence, the giant share of the uncertainty of India's future population is due to fertility uncertainty and to a smaller extent to uncertainty about future child and young adult mortality.

These results for India show that the world's most populous country of the 21st century is likely to simultaneously experience significant further population growth and population aging. The pro portion above age 60 will almost triple over the coming half century. This will pose formidable challenges to old age social and economic support systems. At the same time the total population will continue to grow significantly by some 40 percent, bringing many of the infrastructural problems associated with rapid population growth. The good news is that over the coming decades the pro portion of the total population that is of working age will also increase substantially, thus providing a "demographic window" or "demographic bonus" for more rapid economic development. If this opportunity is used for heavy investments in education and human capital formation (along the lines of the IPCD scenario) this would significantly strengthen India's economic and political standing in the world and improve the quality of life of its citizens.

4 Discussion

The paramount importance of the specific path of the future fertility trends in India on the total population size is an ex post justification for spending a considerable amount of time and effort to capture some of the structural determinants of future fertility trends in India. Whether there will be 200 million more Indians in 2050 is not a trivial issue. As we have shown, this will depend significantly on the future educational efforts in India.

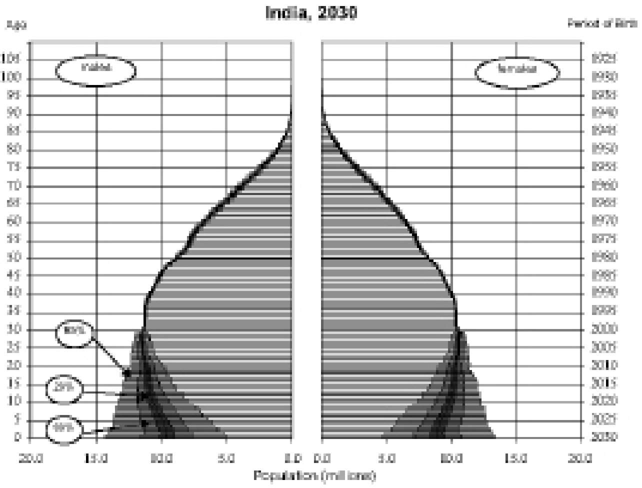

Figure 6. Probabilistic population pyramid for India in 2030.

The analysis presented here has only been a first step in the direction of trying to incorporate this very important structural dimension of population uncertainty into population projections. Much more attention should be given to this and other important structural drivers of fertility decline in developing countries in the future. Here we focused on female education as probably the most important observable source of fertility heterogeneity. Urbanization would be the next logical candidate for such analysis. But it should probably be cross-classified with education (Cao & Lutz 2004).

The great sensitivity of the future level of aggregate fertility to the change in the educational com position of the population raises disturbing questions about the way fertility assumptions are usually derived for developing countries that are in the midst of structural changes of the sort described here for India. When future paths of aggregate-level fertility are being assumed in regular population projections, then these should reflect all possible forces that influence aggregate fertility. It is not clear, however, that without an explicit formal model of the sort presented in this paper, the extent of the effect of these compositional changes can be adequately assessed in a more or less intuitive manner. In principle, this reflects the general problem of describing the dynamics of heterogeneous populations, which can show unpredicted behavior if the heterogeneity is not accounted for. The best strategy thus should be to make sure that at least the observable and most significant measurable sources of heterogeneity are explicitly incorporated in the analysis of population dynamics. In most developing countries education is such a source of heterogeneity that should be made explicit.

In conclusion we can say that the explicit consideration of some of the most important drivers of changes in demographic rates can make a major difference in the way we see the population evolve in the future. This is particularly true in the context of probabilistic population projections, where the uncertainty about the evolution of the structure of heterogeneous populations is added to the uncertainty about demographic trends within each sub-population. This aspect is quantitatively more important in heterogeneous populations, such as India, than in the more homogeneous ones.

How to deal with this issue in the context of specific populations to be forecasted, cannot be deter mined purely by statistical models. It requires deep substantive analysis and inevitably a degree of expert judgment. But in any case we should be careful to base our assumptions on explicit arguments that are open to the usual instruments of scientific review and evaluation.

Acknowledgements

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Probabilistic Population Projections for Austria[1]

Wolfgang Lutz, Sergei Scherbov and Alexander Hanika

The traditional way of dealing with uncertainty in future population trends has been to produce high and low variants of population projections, in addition to a medium variant. There are two serious problems with this approach. First, traditionally only fertility assumptions have been altered for the variants (which is still the case in the UN projections) while uncertainty in future mortality and migration trends remained unaccounted for. Second, the user is not really told what to make of the variants, whether they are supposed to give the bounds of the uncertainty range or simply represent alternative sample paths. Although the user is often explicitly warned that the variants should not be taken as confidence intervals, this seems to be the only logical interpretation for a user being confronted with a most likely case and a range around it.

Several statistical agencies, including the Austrian Central Statistical Office, have recently solved the first problem by considering alternative scenarios that assume different mortality and migration assumptions in addition to the fertility variants. However, little progress has been made so far on the second issue. This paper demonstrates a feasible way of transforming given expert views on the uncertainty about future fertility, mortality and migration trends into a set of fully probabilistic projections that provide the user with information about the likelihood of alternative future population trends. The methodology for doing so is briefly discussed in Lutz et al. (1996; 1997). A sensitivity analysis of some of the assumptions made in the application to Austria, as well as a comparison to alternative methods more heavily based on time series analysis, is given in Lutz and Scherbov (1997). Here only the results can be briefly outlined.

In the case of the Austrian projections, expert opinion on future uncertainty has already been defined through alternative fertility, mortality and migration assumptions for the regular nonprobabilistic projections. For these official projections the Austrian experts defined high, medium and low assumptions for the three components. (The low variant for life expectancy was defined for this study.) Since these assumptions turned out to be symmetric, three normal distributions could be deter mined. The only additional assumptions required concerned the range of all possible future paths to be covered by the high-low intervals. Further discussions with the Austrian experts resulted in the assumption of 90% between high and low values for fertility and mortality (sensitivity analyses with 85% and 95% show that the system is not very sensitive to slightly different percentages). In the case of migration only two-thirds (67%) was assumed because of the uncertainty about future developments in Eastern Europe. The projections were then performed by independently drawing 1,000 times from the three distributions and combining them into 1,000 cohort component population projections. Selected fractiles of the resulting distributions are shown in Figures 1-3 and Table 1.

In summary, the results show that future trends in old-age dependency ratios are much less uncertain than those of total population size, because much of the future course is already preprogrammed in the pre sent age distribution. The probabilistic age pyramid in Figure 3 indicates that in 2030 the uncertainty is lowest for the cohorts born between 1955 and 1975 because they will not yet have entered the high mortality ages strongly affected by uncertainty about future old-age mortality. For the cohorts born between 1975 and 1997

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the range increases owing to migration uncertainty. Of course, for the cohorts still to be born, fertility uncertainty plays a dominant role.

Such information about the degree of uncertainty by age groups is highly relevant, e.g., for present plans in Austria to change the financing structure of the pension system.

This approach to probabilistic projections presents a direct evolution of the current practice of population projections in most statistical agencies and can build on the existing structures of defining assumptions. We anticipate great potential for other national statistical agencies following the Austrian example of "officially" publishing the probabilistic projections in addition to the conventional ones. This adds significant value for some uses of the projections (wherever a cost function is involved, such as in social security), without conflicting with the current practice of projections.

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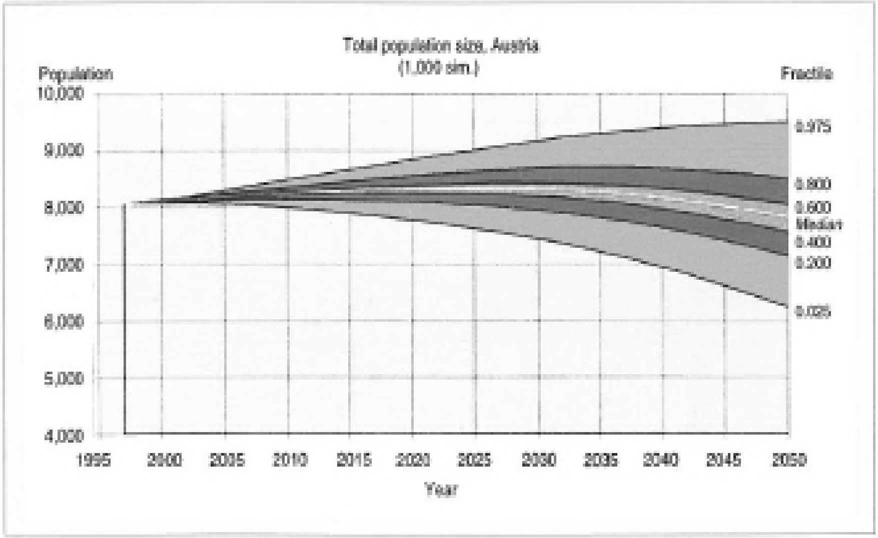

Figure 1. Median and selected fractiles of the probability distribution of the total population size of Austria.

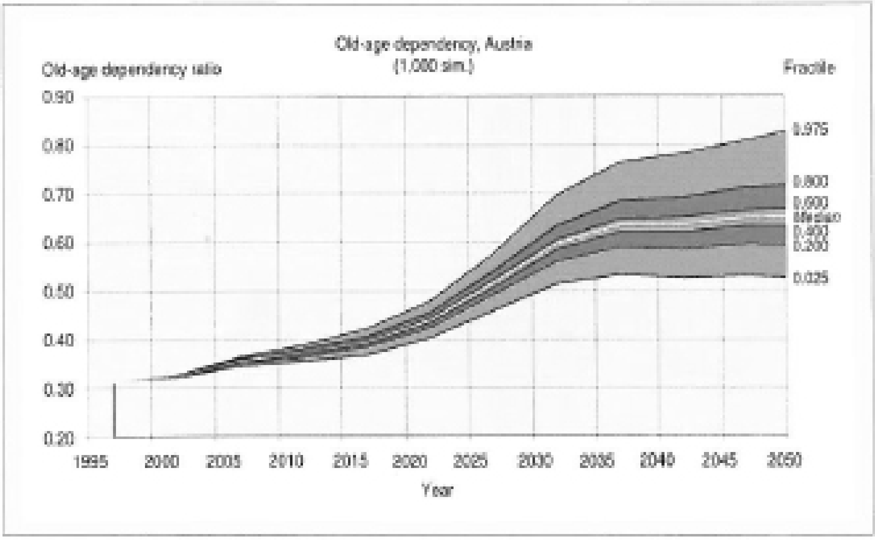

Figure 2. Median and selected fractiles of the probability distribution of the old-age dependency ratio in Austria.

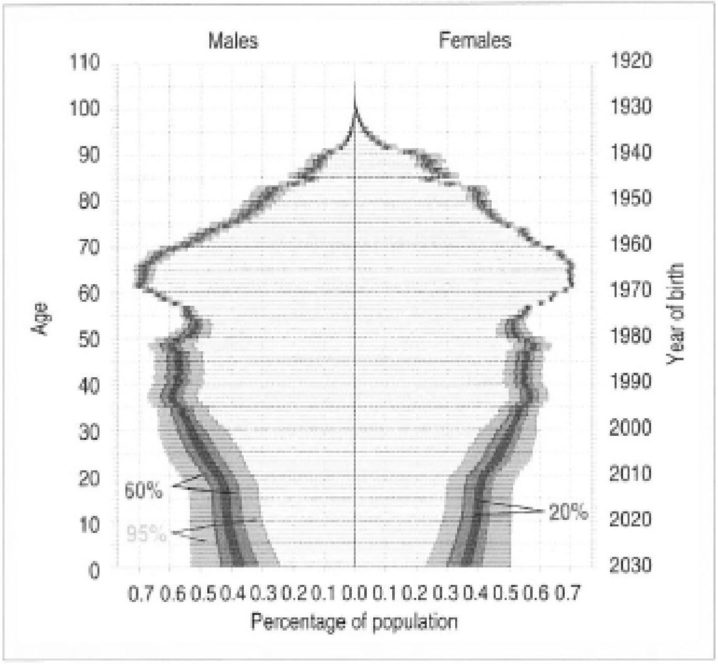

Figure 3. Selected fractiles of the probability distribution of the Austrian age pyramid in 2030.

Table 1. Fractiles of the probability distribution of the total Austrian population, proportion above age 60 and proportion below age 15.

	1997	2010	2030	2050
Total Population				
Median	8.08	8.26	8.29	7.73
Inner 20%		8.22-8.30	8.17-8.42	7.47-7.99
Inner 60%		8.13-8.39	7.91-8.70	7.03-8.45
Inner 95%		7.95-8.55	7.37-9.22	6.08-9.52
Proportion above age 60				
Median	0.197	0.231	0.323	0.344
Inner 20%		0.229-0.232	0.318-0.328	0.336-0.353
Inner 60%		0.227-0.235	0.308-0.339	0.320-0.371
Inner 95%		0.221-0.240	0.287-0.362	0.290-0.416
Proportion below age 15				
Median	0.173	0.149	0.134	0.128
Inner 20%		0.148-0.152	0.132-0.138	0.124-0.133
Inner 60%		0.142-0.156	0.122-0.146	0.111-0.144
Inner 95%		0.132-0.165	0.104-0.162	0.088-0.164

2 Long-Range Scenarios

Introduction

Brian C. O'Neill

Approaches to characterizing future demographic outcomes include probabilistic projections as well as alternative individual scenarios of possible outcomes. Often, these approaches have been pitted against one another, but in fact both are useful and frequently one or the other will be better suited to a particular question or user community. Hybrid methods are possible as well, including conditional probabilistic projections and very large sets of scenarios that can be used in robust decision-making frameworks. Sergei Scherbov's work has extended the frontiers of all three types of approach. The first section of the book contains much of his work on probabilistic projections and hybrid approaches. Here we turn to his work involving long-range scenario methods.

"Scenario" can have a variety of definitions, but typically it refers to an individual projection of the consequences of plausible assumptions about the future. The word "plausible" indicates that there is in fact a connection (albeit a very loose one) to notions of probability. Characterizations of the future that are clearly impossible or have a vanishingly small likelihood generally go by other names: thought experiments, sensitivity analyses, or just plain projections. A (plausible) scenario is a future that has some likelihood of occurring that is large enough to make it worth considering for the purpose at hand. For example, if population scenarios are being used to investigate potential needs for a social security system, it is probably not worth considering a future in which fertility immediately drops to zero. That outcome is so unlikely as to not be worth considering when aiming to create a social security system that is robust against surprises.

Sets of alternative scenarios are employed for a variety of uses. Prominent uses include going beyond a single "best guess" scenario to more fully characterize uncertainty in future outcomes. Such applications typically explore alternative, less likely outcomes that are nonetheless possible and important to consider for planning purposes. Scenarios can also be used to examine specific "what if?" questions relevant to policy design or research. In this case one or two targeted scenarios may suffice: for example, how might a particular population-related policy affect population size and age structure? Further, scenarios can be used to illuminate and extend demographic theory, testing analytical results or extending them into conditions for which analytical solutions are too complex or not available.

Sergei's work on scenarios has involved all of these types of use, and has continued side by side with his work on probabilistic and other approaches.

An early and illustrative example is his 1988 IIASA working paper written with Douglas Wolf, Babette Wils, and Wolfgang Lutz on alternative population scenarios for Europe (Wolf et al. 1988, this volume). Motivated by a desire to go beyond the typical focus on a single most likely outcome, the authors set out to develop scenarios that investigated a number of potential "surprises" that could affect fertility, mortality, or migration. This set of scenarios was distinguished from other efforts, as Nathan Keyfitz writes in his introduction to the working paper, by its "extremely wide range of assumptions regarding births, deaths and migration," assumptions that are "unlikely to be fulfilled, but none of them is impossible," a caution that would turn out to be prescient.

The authors designed a set of assumptions they thought were plausible, if unlikely, and worth considering in research applications or policy considerations that depended on Europe's demographic future. The point was to investigate what sorts of "surprises" relative to a central, "best guess" projection from the UN would have large demographic consequences and which would not. Alternative scenarios included a spike in international migration into the region, an AIDS-driven mortality crisis leading to a drop in life expectancy of 10 years over a 20-year period, and unexpected health care improvements that substantially improved life expectancy beyond the steady rise foreseen in the central UN scenario. In addition, they considered alternative futures in which the total fertility rate either increased temporarily from its mid-1980s level of about 1.85 to about 2.5 driven by a second European baby boom, or continued its decline to 1.4 by 2020. Both of these scenarios differ substantially from the UN central assumption of a gradual increase from 1.85 toward replacement level fertility.

Results showed that the big effects arose from the continued fertility decline scenario and from the AIDS mortality crisis scenario, with other scenarios having much smaller consequences. As it turned out, nothing like the dire AIDS scenario occurred, but fertility in fact declined initially even faster than envisioned in the continued decline scenario before stabilizing recently around 1.6 (a level similar to the one projected in the continued decline scenario for today).

That early work produced a lesson that has been demonstrated over and over from scenario analysis: the importance of considering a wide range of what may be considered unlikely (but possible) outcomes. As recently as 2013, Sergei put this lesson into action again along with Stuart Basten and Wolfgang in producing a set of projections that were unusual for looking far into the future: 2300 (Basten et al. 2013, this volume). It is not uncommon in studies of global environmental change to look well beyond our current century to investigate slow-changing aspects of the physical environment such as sea level, climate, or ecosystem change. At times, it is useful to inform these studies with at least some notion of the range of societal conditions that might exist over such time frames. About a decade earlier, the UN had produced scenarios to 2300, primarily motivated by these types of environmental applications. However, they had used a relatively narrow set of assumptions.

Sergei and co-authors took this as an opportunity to use scenario analysis to produce an improved understanding of what the long-range uncertainty in population growth and aging might actually be. Results illustrate the truly astonishing range of possibilities for the long-term future of humanity. Fertility levels that fall within the range of those that have been observed and that appear in fertility intention surveys, when sustained over time, lead to very large differences in global population size. The scenarios show that it is plausible to imagine a global population of a billion or less within a couple centuries, and it is also possible that there will be tens of billion people on earth. This is useful information, if only to prevent one of the most common and persistent errors of forecasters from all fields: overconfidence and the difficulty of imagining the future as fundamentally different from today.

Other scenario applications are directed less at improving the characterization of uncertainty and more at understanding the drivers of particular demographic outcomes. As an example, I collaborated with Sergei, along with Wolfgang, on my first purely demographic paper (in 1999, this volume), aimed at understanding which aspects of fertility pathways most influenced population size and age structure outcomes. My ultimate interest was in the role that population played in the climate change issue, and in particular how that role would be influenced by future trends in fertility. While it was clear that generally lower fertility pathways led to slower growth and more aging, it was not clear which aspect of a pathway of fertility decline matters most, and when: was it how fast or how far, fertility fell?

Wolfgang, Sergei, and I designed a set of alternative fertility scenarios to disentangle these two aspects, and Sergei carried out the projections. At the time, I was a staff scientist at the Environmental Defense Fund (EDF), a US environmental NGO, and beyond the work itself, the project was significant simply because it involved an environmental scientist at an NGO working jointly with two demographers on a population topic. Such interactions between the research and policy communities related to population-environment issues were rare at the time; our meeting at the EDF offices in Manhattan was one of the early steps leading to much greater collaboration over time.

This work was also significant on its demographic merits alone. As is typically the case with Sergei's work, there is a connection to both the theory and practice of population projection. Long-range population projections typically assume fertility falls to some long-term level and remains constant thereafter. Stable population theory indicates that a population with constant fertility will eventually have a stable age structure and constant growth rate, independent of the fertility path prior to becoming constant. But the size of the population does depend on the fertility history, in a way that is difficult to capture analytically. Scenarios can illuminate this relationship. In addition, the typical assumption in population projections at the time was that the primary determinant of demographic outcomes was the ultimate level of fertility. For this reason, high and low variants varied the long-term fertility level but did not focus on the speed of the transition. There was therefore a practical motivation to investigate this sensitivity as well.

We found that the speed and extent of the fertility decline were related, which is relatively intuitive in hindsight. In a country with initially high fertility, if the long-term fertility level is very low (i.e., the extent of decline is large), population size is quite sensitive to the rate of decline. That sensitivity lessens if fertility does not fall as far. A geographic analogy is that the speed of a trip matters much more if the destination is far away than if it is close by. We also showed that the speed of the transition dominated the population size results this century, which is the focus of most environmental applications of population scenarios, while the extent dominated results in the longer-term future. This work highlighted the importance of getting the speed of the fertility transition right, especially if the extent of the fertility decline might lead to lower levels than previously thought, a possibility being taken more and more seriously at that time.

In a later collaboration, published as a Policy Forum in *Science*, the three of us took up the issue of low fertility and the potential for population decline in Europe, motivated not just by implications for the environment but also for social systems (Lutz et al. 2003, this volume). Here Sergei carried out scenario-based projections of European population to identify forces driving population change and to quantify the potential for policies to influence that change. Could policies that discourage delays in child bearing have a quantitatively significant effect?

The scenario analysis showed that a little-recognized threshold had been crossed in Europe around the year 2000, from positive to negative population momentum. Negative momentum refers to a tendency for population to decline in the long term due to its current age structure, as a result of previous low fertility that made the generation of children smaller than the generation of parents. The scenarios demonstrated that this force for decline would grow over time if fertility remained low, becoming increasingly difficult to counteract through longer life expectancy or immigration. In particular, negative momentum as of 2000 was relatively small; if no other forces for change acted on the population, this momentum would lead to a decline of about 15 million people in the long-term population size. However, it could grow to 88 million by 2020 if fertility remained low.

We further examined the case of hypothetically halting the delay in childbearing that was partly responsible for the low fertility, estimating that such a halt would increase fertility from 1.5 (the level in 2000) to 1.8. Sergei's results showed that this change would cut the 88 million decline due to negative momentum nearly in half, and substantially ameliorate the effect of low fertility on aging. Thus, the answer to the question about the potential effectiveness of policies related to delayed childbearing was yes, they could have significant effects on population outcomes.

In retrospect, looking at alternative future fertility outcomes has proved important. While we are not quite at 2020 yet, actual fertility in the EU has looked much more like the continued low fertility scenario (around 1.5 or 1.6) than any of the fertility increase scenarios, and thus negative momentum has likely increased to a force for a nearly 90 million person decline, as Sergei originally calculated.

Joshua Goldstein teamed with Sergei and Wolfgang in a paper in *Population and Development Review* to further test the robustness of these conclusions by considering additional factors at play, motivated in part by theoretical considerations (Goldstein et al. 2003, this volume). Population theory for subreplacement fertility conditions indicates that a longer generation length (due to delayed childbearing) should slow population declines, rather than hasten the, as occurred in our previous scenarios due to lower period fertility. Might this effect be quantitatively significant, and (at least partly) offset the population decline due to delayed childbearing? Also, our results had ignored the possibility that delayed childbearing would lead to a reduction in cohort fertility (a so-called tempo-quantum interaction effect). In the presence of such an interaction would results significantly change?

A set of targeted scenarios, specifically designed to address this question, complemented an analytical analysis to conclude that the generation-length effect was small, at least on a decades-to-century scale (but would eventually offset the effect on period fertility, after several centuries). But the tempo-quantum effect was potentially large: if delayed childbearing leads to lower (not just later) cohort fertility, this effect can dominate results. Here Sergei's scenario calculations illuminated and extended population theory, and usefully clarified the robustness of a policy-relevant analysis.

Today, there is just as much need for population scenarios as there has been over the full span of Sergei's career, for characterizing uncertainty, illuminating theory, facilitating collaboration with other disciplines, and informing policy. If the last several decades are any indication, Sergei is sure to be at the forefront of these efforts.

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The Long-Term Effect of the Timing of Fertility Decline on Population Size[1]

Brian C. O'Neill, Sergei Scherbov and Wolfgang Lutz

Long-range population projections derive from underlying assumptions about the future paths of fertility, mortality, and migration. Fertility scenarios are usually constructed by choosing a level at which fertility is assumed eventually to become constant and a path from the current to the eventual fertility rate. Stable population theory (Keyfitz 1968) shows that populations experiencing constant fertility, under the assumption of constant mortality and migration, tend toward a fixed age structure and growth rate that are independent of the history of vital rates. However, the long-term population size is determined by both the eventual fertility level and the transition path. Two projections with identical eventual fertility rates but different transition paths will produce population sizes that differ in the long term by a constant proportion.

For example, long-range population projections that assume universal convergence to a replacement-level fertility rate show that doubling or halving the length of the transition from current to eventual fertility produces a range in population size in 2150 of about ±20 percent (Bos et al. 1994). In contrast, projections in which eventual fertility rates vary by half a birth per woman around a central estimate produce global populations that differ by ±50 to 70 percent in 2100 and by more thereafter (United Nations 1998). Taken together, these results have been interpreted as implying that the timing of the fertility transition has a relatively unimportant effect on long-term population size. Nevertheless, no long-range projections have systematically investigated the importance of the path of fertility decline as distinct from the effect of the eventual fertility level, and theoretical analysis (Keyfitz 1971) has been limited to the case of eventual replacement-level fertility.

In this note, we first demonstrate the effect of varying the assumed length of the fertility transition - an indicator of the rate of change in fertility - for different eventual levels of the total fertility rate (TFR) by carrying out an extensive set of projections for the single region of North Africa. Figure 1 shows the results of 35 projections for the region in which, starting from the age distribution of 1995, the eventual TFR was varied from 1.0 to 3.0 births per woman, while the length of the transition from the current total fertility rate of 4.24 to the eventual TFR was varied from 20 to 80 years. Each curve shows the results of projections in which fertility converges to a different eventual fertility level. The length of the fertility transition (assumed to be linear) is given along the x-axis, and results are normalized to the population size assuming a 50-year transition. Migration is assumed to be zero, and mortality follows a central scenario (Lutz 1996). The projections cover a period of 155 years from 1995 to 2150.

The scenario assuming the lowest eventual fertility level shows the greatest sensitivity to the speed of the decline. If eventual TFR is assumed to be 1.0, then as the length of transition varies by ±30 years around a central value of 50 years, population size varies in the long term by +145 to -60 percent. In contrast, if eventual TFR is 3.0, long-term population size varies by +21 to -17 percent around its value in the 50-year transition scenario. These differences are achieved at different times depending on the length of the transition. In general, much of the difference is apparent within two generations of the time at which

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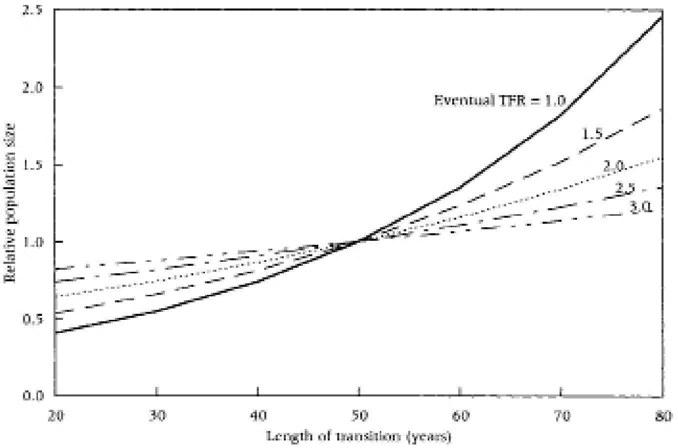

Figure 1. Population of North Africa projected from 1995 to 2150 assuming various levels of the total fertility rate (TFR) at which fertility eventually stabilizes and differing lengths of transition from the current to the eventual fertility rate. For each set of projections assuming a given eventual fertility rate, population size is shown as a ratio to the population size assuming a 50·year fertility transition

fertility becomes constant. We report results for 2150, by which time the relative sizes of populations projected with different transition lengths but common eventual fertility rates have become nearly constant in all cases. Beyond 2150, relative population sizes change little. However, absolute population size, changing at a constant rate, will become either extremely large or extremely small if the eventual fertility rate remains constant above or below replacement level; we make no assumptions as to the likelihood of these outcomes. For reference, Table 1 shows the absolute size of the projected population of North Africa in 2150 for a selection of the scenarios considered here.

The results of the analysis are explained by the fact that the difference between the initial and the eventual fertility rate over the course of the transition is the key factor in determining the impact of the path on population size. The lower the eventual fertility, the greater the rate of change in fertility over the transition, and the greater the impact of

Table 1. Projected population of North Africa in 2150, in millions, under various assumptions concerning the length of fertility transition from the current level of the TFR of 4.24 to various levels at which fertility eventually stabilizes

	Length of transition		
Eventual total fertility rate	**20 years**	**50 years**	**80 years**
1.0	24	59	145
1.5	96	178	332
2.0	279	432	669
2.5	679	916	1240
3.0	1460	1770	2140

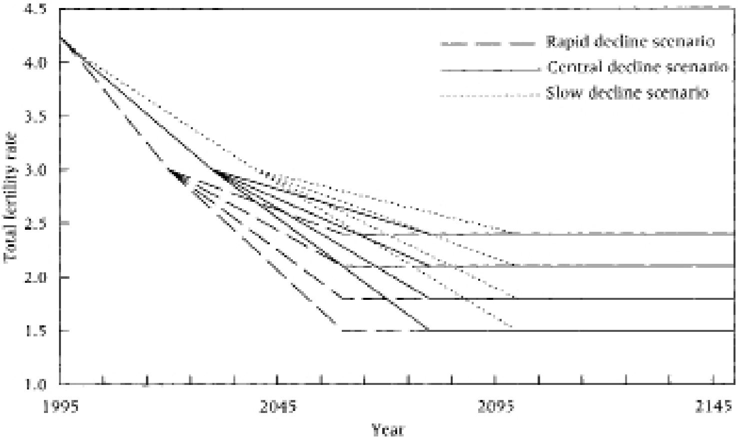

Figure 2. Scheme of the alternative fertility scenarios for developing regions, 1995-2150, illustrated with the example of North Africa, where the initial level of TFR is 4.24

Note: See discussion in text.

altering that rate on population size. By analogy to geography, this relationship is equivalent to the observation that the more distant a geographic destination, the more important travel speed becomes.

To investigate the effect within the context of an existing set of longterm population projections, we constructed a set of 12 scenarios by modifying the central scenario from the projections of the International Institute for Applied Systems Analysis (IIASA; see Lutz 1996), as shown in Figure 2 for the example of North Africa. In the four central scenarios, represented by solid lines in the figure, TFRs in regions currently above replacement level follow the IIASA central scenario to 2030-35, then reach an eventual level of 2.4, 2.1, 1.8, or 1.5 in 2080-85, the time interval used to specify eventual constant fertility in the IIASA projections. We tested the sensitivity of each scenario to the timing of the decline by defining two alternative scenarios involving a rapid and a slow decline to each of the four assumed eventual fertility levels. Dashed lines represent the rapid fertility decline scenarios in which the TFR achieved in 2030-35 and 2080-85 in the central scenario is achieved 10 and 20 years earlier, respectively. Dotted lines represent the slow fertility decline scenarios in which these TFR values are achieved 10 and 20 years later, respectively. For all scenarios, mortality and migration assumptions are identical with the paths specified in the central scenario.

Table 2 shows that if the high-fertility regions stabilize near replacement level, an acceleration or deceleration of the fertility decline would cause an eventual change in the combined population size of all regions of -16 percent to +21 percent, similar to the effect found in previous studies (Bos et al. 1994). If the eventual fertility rate is assumed to be 0.3 births per woman higher, the impact on population size weakens to -11 percent to +13 percent. In contrast, if eventual fertility stabilizes below replacement level at 1.8, the impact on population size strengthens to -23 percent to + 31 percent, and strengthens further to -31 percent to +45 percent if eventual TFR is 1.5. Thus, a lowering of eventual fertility by 0.6 births per woman relative to replacement level roughly doubles the effect of altering the

Table 2. Percent difference in projected long-term population size in developing regions assuming rapid (R) and slow (S) fertility declines relative to population size in a central scenario as dependent on the assumed level of the eventual stable total fertility rate" and on the speed with which that rate is attained

	TFR = 2.4a		TFR = 2.1		TFR = 1.8		TFR = 1.5	
Region	R	S	R	S	R	S	R	S
North Africa	-17	+20	-23	+29	-29	+40	-36	+55
Sub-Saharan Africa	-23	+29	-28	+39	-34	+51	-40	+66
Latin America	-3	+3	-10	+10	-17	+20	-26	+34
Central Asia	-13	+15	-20	+25	-26	+36	-34	+51
Middle East	-19	+24	-25	+33	-31	+44	-37	+59
South Asia	-8	+9	-13	+15	-21	+25	-28	+39
Pacific Asia	-2	+2	-8	+9	-16	+18	-24	+31
Total	-11	+13	-16	+21	-23	+31	-31	+45

[a]The eventual total fertility rate in Latin America, South Asia, and Pacific Asia is assumed to be identical with its 2030-35 value of 2.35.

Table 3. Projected population size of developing regions in 2150, in millions, as dependent on the level at which fertility eventually stabilizes according to the central scenario

	Eventual total fertility rate[a]			
Region	**2.4**	**2.1**	**1.8**	**1.5**
North Africa	865	637	459	321
Sub-Saharan Africa	2079	1519	1084	750
Latin America	1409	1073	758	522
Central Asia	303	222	159	111
Middle East	1088	812	593	422
South Asia	3051	2326	1642	1126
Pacific Asia	1146	875	619	425
Total	9941	7465	5313	3677

[a]The eventual total fertility rate in Latin America, South Asia, and Pacific Asia is assumed to be identical with its 2030-35 value of 2.35.

length of the transition by 20 years. The magnitude of such relative differences varies region to region, as detailed in Table 2. In Latin America and Pacific Asia, for example, the impact of a change in the timing of fertility decline roughly triples at lower eventual fertility levels. Table 3 provides absolute sizes of populations in 2150 according to the central scenario for each eventual fertility level.

These results demonstrate that a given change in the speed of the fertility transition has a larger impact on population size the lower the assumed eventual fertility rate. It is also true that a given change in eventual fertility itself has a larger impact the lower the eventual fertility rate in a reference case. For example, changing eventual fertility by 0.3 births per woman from a reference case in which eventual fertility is low will have a larger impact than the same change from a case in which eventual fertility is high. We therefore investigated the relative sensitivity of projected population size to these two factors.

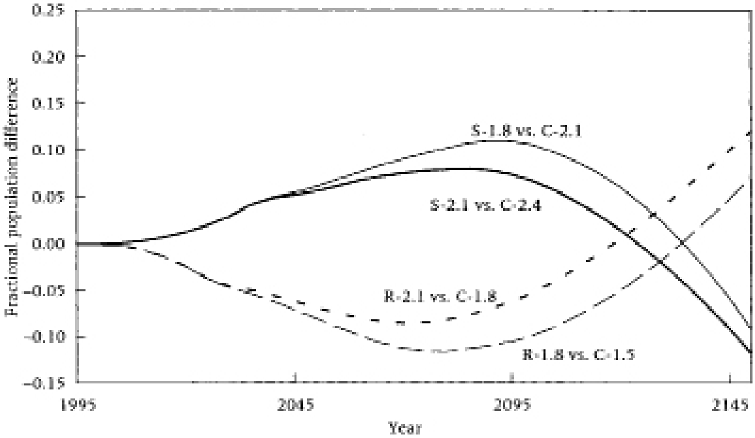

Figure 3. Illustration of the relative impact of the speed and extent of the fertility transition on the projected population size of the developing regions by comparing scenarios differing in the eventual level of the total fertility rate and the speed with which that level is attained

Note: R, C, and S represent the rapid, central, and slow fertility decline scenarios; 2.4, 2.1. 1.8, and 1.5 indicate the eventual fertility level achieved in each case.

Figure 3 illustrates the relative impact of the speed and extent of the fertility transition on the projected population size of the developing regions. It demonstrates both that a change in transition speed has a greater impact at lower eventual fertility levels and that its impact increases relative to the effect of a change in the eventual fertility rate. The thick solid line in the figure represents the difference between the increase in population (relative to the "central 2.1" scenario) brought about by slowing the fertility transition by 20 years and the increase caused by raising the eventual fertility level from 2.1 to 2.4 while holding the transition length constant. This difference is positive between 1995 and about 2125, indicating that the change in the speed of the transition dominates the increase in eventual fertility in terms of its effect on population size. After 2125, the change in eventual fertility is the dominant influence. The thick dashed line compares the effect of speeding up the fertility transition by 20 years to the effect of lowering the eventual fertility rate from 2.1 to 1.8. It shows that between 1995 and about 2120, speeding up the fertility decline reduces population size by more than reducing eventual fertility. After 2120, lowering the eventual fertility rate is the dominant influence.

The two thin lines in Figure 3 show a parallel set of results that demonstrate how these relationships change when an eventual fertility rate of 1.8 instead of 2.1 is taken as a reference point. Changes in the speed of fertility decline are dominant for a longer period of time, relative to changes in eventual fertility, than is the case when the reference eventual fertility rate is at replacement level.

Our analysis of the impact of changes in the timing of the fertility transition could easily be extended to include regions in which fertility is currently at or below replacement level. However, concern in low-fertility societies centers less on population size than on issues related to aging (de Jong-Gierveld et al. 1995; van Praag & van Dalen 1994); and while the rate of aging will be affected by the path and by the eventual level of fertility, the long-term age structure is independent of the path over the next several decades. This implies that a more rapid pace of fertility decline is not achieved at the expense of a higher eventual proportion elderly.

These findings place new emphasis on the task of constructing scenarios for fertility decline. As demographers begin to take into account the possibility of eventual subreplacement-level fertility in long-term population projections (Bongaarts 1998; Lutz 1996), they need to be cognizant of the significant role the path of fertility decline will play in determining the size of the ultimate stable population. Our results also have implications for policies seeking to take into account the consequences of population growth for economic change and the environment (O'Neill et al. 2001; Vitousek et al. 1997). Finally, while considerable aging will take place under all scenarios of future population growth, the speed of fertility decline over the coming decades will make a significant difference to the long-term levels of population size that will accompany older age structures.

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Long-Term Population Decline in Europe: The Relative Importance of Tempo Effects and Generational Length[1]

Joshua Goldstein, Wolfgang Lutz and Sergei Scherbov

It has recently been suggested that ending the increase in the average age of childbearing in Europe would have a substantial effect on population dynamics by slowing population decline and aging. On the other hand, stable population theory suggests that under conditions of subreplacement fertility, longer generation length would imply slower shrinking, and thus produce a larger population in the long run. This note compares the relative importance of these two effects analytically and with actual data from the European Union.

In a recent contribution to the Policy Forum of Science entitled "Europe's population at a turning point," Lutz, O'Neill, and Scherbov (2003) showed that Europe has just entered a period of negative population momentum a tendency to decline in response to an old age structure, even if fertility were to instantly increase to replacement level. They tried to quantify the effect of continued increases in the mean age of childbearing (the so-called tempo effect) on the absolute number of births and future population dynamics in the 15-country European Union. They used as a baseline a scenario in which the tempo effect ends instantly-that is, the mean age of childbearing remains constant-and, as a result, the period total fertility rate (TFR) increases from 1.5 to 1.8. This baseline was compared to a continuation of the tempo effect for 10, 20, 30, or 40 more years, which would keep the TFR lower by 0.3 over those periods.

Lutz et al. found that the effects on population dynamics of continued low period fertility depressed by a continued increase in the mean age of childbearing are substantial. One method of calculation attributed 45 percent of future population decline to a continuation of the tempo effect until 2020. The consequences of continued increase in the mean age of birth on future population aging in the EU are also large. Seen from the perspective of the working-age population, defined as ages 15 to 64, continued delay of 10 to 40 years would imply that, ceteris paribus, an additional 500 million to 1,500 million person-years of working-age persons would be needed to support the elderly population over the rest of the century, as compared with the no-delay scenario.

The demographic consequences of later childbearing have political implications. While governments in Europe are increasingly concerned about possible negative consequences of current low birth rates, there is also pronounced public resistance to any direct government interventions in the choice of one's family size, which is considered a private matter. In this context, policies that aim to influence the timing of births rather than family size might be more acceptable. Health benefits might provide an additional rationale for such policies, given that a continued delay in childbearing has led not only to burgeoning numbers of infertility treatments but also to increasing medical concerns about health risks for mothers and children associated with late pregnancies.

The conclusion of Lutz, O'Neill, and Scherbov that halting the trend toward higher mean ages of childbearing would significantly moderate population aging and decline of population size in Europe (over the rest of this century), however, seems to be in conflict with one of

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the implications of stable population theory.[2] In a stable population with fertility below replacement level, a higher mean age of childbearing means a slower shrinking; a lower mean age of childbearing accelerates the process of shrinking through a faster succession of generations.

One would expect that the consequences of the tempo effect are more pronounced in the near future while those of a changing mean length of generation would only show up in the longer run. But this intuitive assessment does not make precise the consequences of possible policies aimed at influencing the mean age of childbearing. In this note, we quantify the effect on population size and aging of changing fertility timing, first through an analytical examination of this issue and then using numerical simulations applied to the current demographic situation of the European Union.

An analytical answer

Changes in the mean age of childbearing can influence the number of births through several distinct pathways. First, the tempo effect of advancing or postponing births has an immediate effect on the number of births in a calendar period (Bongaarts & Feeney 1998). Second, as suggested above, the generation-length effect will have consequences for the long-term population growth rate. Finally, changes in the timing of childbearing may influence the total fertility achieved by cohorts over their lifetime, with couples who start earlier having more children than couples who start late. This change in cohort fertility that accompanies changes in timing is known as the tempo-quantum interaction effect.

A model taking into account these three factors considers the number of births *B*(t)* at some future time *t* that result from a change in the mean age of childbearing relative to the number of births *B(t)* that would have occurred had timing remained constant. Assuming the three factors are independent, then for *t* long after fertility timing stops changing,

$\frac{B*(t)}{B(t)}$ = tempo effect x generation-length effect *(t)* x quantum effect *(t)*,

where the quantum effect *(t)* stands for the tempo-quantum interaction effect at time *t*. Note that the tempo effect is a one-time effect, whereas the generation-length and tempo-quantum interaction effects persist because they influence the underlying intrinsic rate of growth. In the case of a growing population, increasing the mean age of childbearing will depress all three factors. However, in the case of a shrinking population, later childbearing will depress future births through the tempo and tempo-quantum interaction effects, but inflate future births via the generation-length effect. Our goal is to explore which of these offsetting effects dominates, and when.

The relative magnitude of each of these three effects can be estimated fairly easily. For illustration, we consider the case of contemporary western Europe, where the cohort net reproduction rate (NRR) is roughly 0.9 and we take women's mean age of childbearing as 29 years. We investigate the consequences of a gradual increase in the mean age of childbearing to 33 years.

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[2] We thank Paul Demeny for bringing this point to our attention at the 2003 Annual Meeting of the Population Association of America. In the context of a discussion of European population trends he writes:

In the short and medium term, transition toward a lower mean generational length would be growth-promoting. But if fertility remains below replacement, the negative intrinsic growth rate would deplete the population more speedily, since the succeeding smaller and smaller generations would replace one another more quickly. A higher generational length would, in the long run, stretch out the decline somewhat, moderating its annual tempo. (Demeny 2003, p.3)

In the short term, higher ages of childbearing will reduce the number of births via the tempo effect. Even after the postponement of fertility comes to an end, the birth stream will continue to be smaller than it otherwise would have been, because the short-term decline in births will echo into subsequent generations. Goldstein and Schlag (1999) found that the longterm effect will be inversely proportional to the change in the mean age of childbearing.[3] Specifically, an increase in the mean childbearing age from 29 to 33 years will reduce the long-term number of births by a factor of 1 - 29/33, or about 12 percent, relative to what would have occurred had the childbearing timing remained constant.

The generation-length effect is also quantifiable. From stable population theory, the intrinsic growth rate is approximately log(NRR) / μ where the mean age of childbearing μ is used as an estimate of the mean length of a generation in the stable population. Taking derivatives with respect to μ gives -log(NRR) / μ^2 Continuing our numerical example, an increase of one year in mean age will slow the rate of population decline by about -log(.9) /292 = 12/100,000. A four-year increase slows the rate of decline from -0.36 percent to -0.32 percent. This is quite a small effect, less than 1/20th of one percent.

We can use these estimates of the tempo effect and generation length to ask how long it will take the generation-length effect, which influences the exponential growth rate over time, to overwhelm the one-time longterm effect of tempo. In our example, it will take about 250 years for the 1/20th of one percent change in the annual growth rate to offset the 12 percent change in the birth stream. For the next two or three centuries, however, the tempo effect will dominate.

Finally, we can consider the behavioral and biological effect of changes in women's timing on the total number of children born over women's lifetime. This is a difficult quantity to estimate, since changes in timing have also been accompanied by changes in fertility preferences. However, Kohler et al. (2001) have found that an increase of one year in the mean age of birth lowers cohort fertility by about 3 percent. Although such estimates are necessarily imprecise, their magnitude suggests that the total fertility effect will far outweigh any generation-length effect. In our example, increasing the mean age of childbearing from 29 to 33 years would reduce the NRR from 0.9 to about $0.9*(0.97)^4$ = 0.80. Such a change in lifetime fertility would nearly double the rate of population decline from -0.36 percent to -0.68 percent, even after taking into account the moderating effect of longer generation length.

The analytical results suggest that the growth effects of changing generation length will be of minor importance. It will take several centuries for growth effects to reverse the initial tempo effect on births. Furthermore, the effect on growth rates is likely to be more than offset by changes in lifetime fertility.

It is possible to perform more exact analytical calculations by taking into account the full detail of the starting age structure. However, the complexities of such calculations make it convenient to turn to simulation to assess the effect of changes in fertility timing on population sizes in Europe. An added benefit of the simulations is that they allow one to see transient effects resulting from shifts in fertility rates in addition to the long-term impacts. They also allow us to look at changes in population age structure over time.

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[3] Goldstein and Schlag (1999) give the result for stationary populations. A full proof of the result for populations with non-zero growth rates is given in "Proof accompanying 'longer life and population growth,"' available at <<http://opr.princeton.edu/-josh/stretchproof.pdf>>. The proof assumes that the intrinsic growth rate associated with cohort net fertility is constant. Standard results from renewal theory can also be used.

A numerical answer through simulation

The calculations presented below refer to the population of the European Union with its 15 member states as of 2003. They use the same baseline data in terms of the initial age distribution and fertility and mortality conditions as in the calculations by Lutz, O'Neill and Scherbov (2003) discussed above. As in that paper, we also consider a tempo effect of 0.3 in terms of TFR, which corresponds to an increase in the mean age of childbearing of 0.2 years per year or 2.0 years per decade starting with a mean age of 29 years in 2000 (Bongaarts 2002). Alternative calculations were performed for tempo effects lasting 0, 10, 20, 30, and 40 years. The figures below show only the cases of zero and 20 years of tempo effects, which clearly illustrate the main points.

The figures give three distinct scenarios:

Scenario I shows the case of an immediate end to the factor causing the tempo effect, that is, no further changes in the mean age of childbearing are assumed, hence period TFR is taken as constant at 1.8.

Scenario 2 shows the case in which the current tempo effect is assumed to continue for 20 more years without having an effect on total cohort fertility (i.e., no interactions). The period TFR is at 1.5 until 2020 when it increases to 1.8. In this case the curve of age-specific fertility rates is simply moved to the right by two years per decade. This also implies that birth rates above age 40 would increase considerably, which does not seem very realistic unless medically assisted conception becomes far more common than at present.

Scenario 3 assumes a continuation of the tempo effect as in Scenario 2, but it also assumes that not all postponed births will be recuperated, hence there is a negative effect (tempo-quantum interaction) on total fertility. In this scenario we apply the simple method of proportionally reducing the age-specific fertility rates by 3 percent (the Kohler et al. estimate discussed above) for each year the age profile is shifted to the right, that is, to higher ages of childbearing.

We also applied more complex approaches that consider the nonlinearity of the tempo-quantum interaction attributable to the fact that at higher ages declining fecundability results in a greater reduction of fertility as women more closely approach a biological limit. In other words, an increase in the mean age of childbearing from 25 to 26 years should have a lower effect on the quantum than a shift from 31 to 32. Since different approaches we applied also resulted in fertility reductions of around 3 percent per year f or a shift starting around the current European mean age of 29 years, we decided to use the simpler linear assumption for the illustrative calculations in this note.

We emphasize that the three scenarios have been defined in order to analyze specific features of population dynamics and should not be mistaken for plausible or even likely future paths. The assumptions of a closed population with no further mortality changes and constant fertility after 2021 are certainly not plausible assumptions for the future of Europe, but they are useful for illustrating some important points. The projections were run for single-year age groups in single-year time steps.

Figure 1 gives the total population size of the current EU15 for these three scenarios over the next four centuries. Such a long time horizon is necessary in order to appropriately assess the long-term impacts of the different effects and compare them to the analytical reasoning given above. The figure clearly shows that over the first two centuries the positive effect of stopping the delay in childbearing (Scenario 1) clearly outweighs the effect

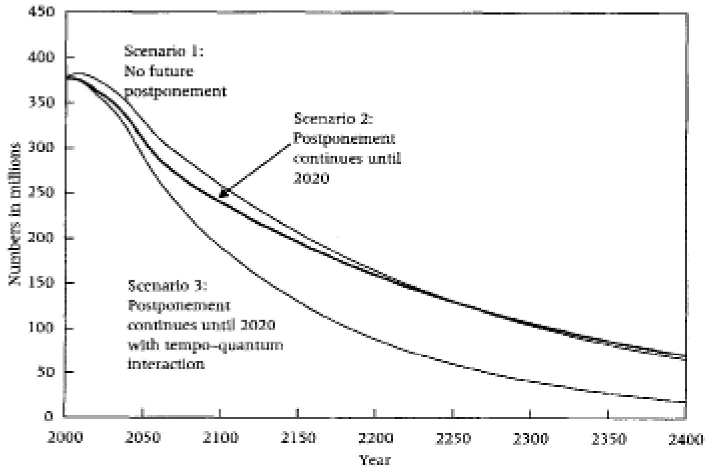

Figure 1. Total population size of EU15 under three childbearing scenarios over four centuries

Note: Scenarios are illustrative, assuming no 1nortality decline and no migration. See text for details.

of a longer mean length of generation in the case of 20 years of further delay (Scenario 2). Only during the twenty-third century does the generation-length effect catch up and only after 2300 does it dominate (in the case of no tempo-quantum interaction), but the difference between the two lines is much smaller than during the twenty-first century. Scenario 3, assuming a depressing effect of a higher mean age of childbearing on total fertility, lies far below the two other curves. This clearly confirms the view expressed in the analytical section that the presence of such a depressing tempo-quantum interaction effect completely dominates the picture, and the long-term positive effect of a longer generation becomes marginal.

Figure 2 gives the trends in old-age dependency ratios (65+/15-64) generated by the same three scenarios. It extends only to 2150 because the stabilization of age structure under constant fertility and mortality conditions makes the picture less interesting in the longer run. This figure dearly confirms that with respect to population aging the tempo effect dominates the effect of longer generation length. A striking result is that for about half of the twenty-first century (from 2025 to 2075), the delay scenario (Scenario 2) has significantly higher dependency ratios than the no-delay scenario (Scenario 1), implying larger pension burdens for an extended period preceding the eventual convergence of the dependency ratios.

The comparison of Figures 1 and 2 also illustrates an important feature of stable population dynamics that is often forgotten by commentators on long-term population and environment trends. Because projections show that over the coming decades population aging in Europe will go hand in hand with population decline (unless large-scale immigration stops the decline), people unfamiliar with stable population theory tend to see these two trends as inseparable twins. On the global level one often hears the view that population aging (in the sense of an ongoing process toward an older and older population) is the price paid for limiting population growth (after an initial beneficial "demographic bonus"). But our long-term scenarios serve as a re minder that this is only true during a transitory period

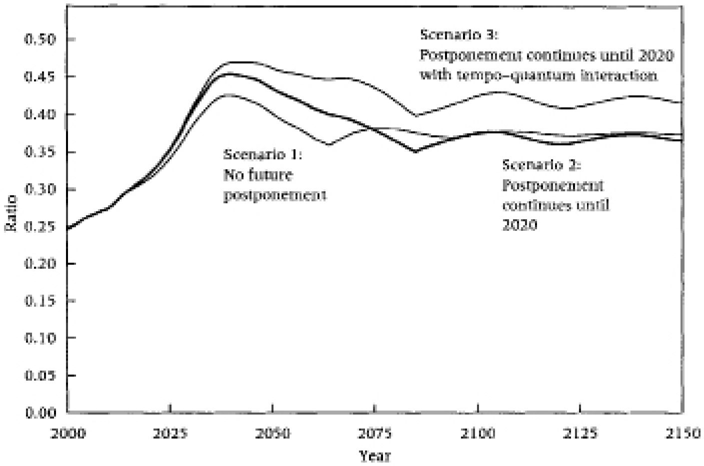

Figure 2. Old-age dependency ratio of EU15 under three childbearing scenarios over one and a half centuries

Note: Scenarios are illustrative, assuming no mortality decline and no migration. See text for details.

of some 80 years. After that, we could have a situation of further declining population size the dream of many ecologists-without having to pay the price of further aging, as distinct from an admittedly rather aged population. As Figure 2 shows, constant fertility even at low levels will result in a peak of the old age dependency burden around 2040 in Europe, still a consequence of the baby boom, to be followed by a moderate decline before stabilizing. This insight is clearly relevant for global climate change models that do have a time horizon of centuries, that see population size as a key driver of greenhouse gas emissions, and that consider population aging an obstacle to societies' capacities to adapt to unavoidable climate change.

Conclusions

In this short note we have demonstrated analytically and through a set of long-term population scenarios that a halt to the current tempo effect in Europe would have significant long-term moderating effects on population decline and aging. The objection that a continued postponement of childbearing also increases the generation length and therefore, under subreplacement fertility conditions, would also lead to slower population decline is theoretically correct but empirically unimportant for the next two centuries. Furthermore, it is likely that later childbearing will itself reduce total cohort fertility. Taking this effect into account overwhelms any effect of generation length.

We did not address the difficult question of what kinds of policy intervention might end further delays in childbearing or even decrease the mean age of childbearing over the coming decades. These issues will need further research and discussion. But this note prepares the demographic groundwork for such a discussion in demonstrating unambiguously that an end to further postponement of childbearing does have significant positive effects both on population size and on reducing the burden of population aging over the coming decades and in the long term. These benefits would be also enjoyed for a fairly long period into the future.

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Europe's Population at a Turning Point[1]

Wolfgang Lutz, Brian C. O'Neill and Sergei Scherbov

Europe has just entered a critical phase of its demographic evolution. Around the year 2000, the population began to generate "negative momentum": a tendency to decline owing to shrinking cohorts of young people that was brought on by low fertility (birthrate) over the past three decades. Currently, the effect of negative momentum on future population is small. However, each additional decade that fertility remains at its present low level will imply a further decline in the European Union (EU) of 25 to 40 million people, in the absence of offsetting effects from immigration or rising life expectancy. Governments in Europe are beginning to consider a range of policy options to address the negative implications of population decline and rapid aging (Lutz et al. 2001; Bagavos & Martin 2001). Social policies and labor laws aimed at halting the further increase in the mean age of childbearing—which contributes to low fertility—have substantial scope for affecting future demographic trends. They also have an additional health rationale because of the increasing health risks associated with childbearing in older women.

Negative Momentum and Low Fertility

Population momentum measures the effect of the current age structure on future population growth (Frejka 1968; Keyfitz 1971). A young population has positive momentum (a built-in tendency to grow). An older population can have negative momentum when low fertility leads to smaller numbers of children than of parents, locking in future decreases in the number of parents and a tendency toward population decline. Momentum can be calculated by performing a hypothetical projection in which all forces for change in population size except age structure are removed[2].

We find that for the 15 member countries of the EU, low fertility brought the population to the turning point from positive to negative momentum around the year 2000. Currently, negative momentum is small (see Figure 1); population even grows for 15 years in our momentum projection before declining, because of the large numbers of people born during the baby boom of the 1960s. However, if the current fertility rate of around 1.5 births per woman persists until 2020, negative momentum will result in 88 million fewer people in 2100, if one assumes constant mortality and no net migration.

Fertility is currently low in Europe for two reasons: first, women are delaying births to later ages [the tempo effect (Ryder 1964; Bongaarts & Feeney 1998)], and second, even after adjusting for this delay, fertility is below the level necessary for each generation to replace itself fully (low adjusted fertility). Delayed childbearing does not affect the total number of children women have over the course of their lives, provided they do not forgo postponed births altogether. However, it reduces the number of children born during the period in which delay is occurring, which lowers birth rates in that period and contributes to the aging of the population.

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[2] Specifically, fertility is assumed to move immediately to, and remain at, about two children per woman, the level that would stabilize population size in the long run; mortality is held constant; and migration is assumed to be zero.

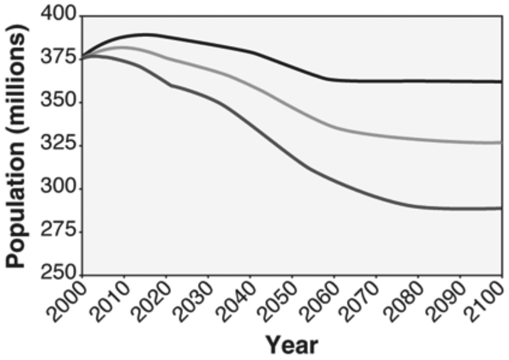

Figure 1. Negative momentum: effect of 20 more years of low fertility on population size in the EU. Population of the 15 member countries of the EU if one assumes that fertility immediately increases to replacement level and remains constant thereafter (black line) or that fertility remains at 1.5 (red line) or 1.8 (pink line) until 2020, when it rises to replacement level.

The population decline of 88 million resulting from 20 years of low fertility can be separated (Fig. 1) into contributions from the tempo effect and from low adjusted fertility. The tempo effect is assumed to be 0.3 children per woman, roughly consistent with recent experience in 10 EU countries for which data are available (Bongaarts 2002)[3]. Postponement of births may continue, because many social and economic factors still favor later childbearing (Kohler et al. 2002). Adjusted fertility is assumed to remain constant at 1.8. Given these assumptions, if increases in the mean age of childbearing were halted, the period fertility would rise from 1.5 to 1.8. Our simulations show that, under these conditions, substantially less negative momentum is generated, and ultimate population size is only 49 million lower than today's. Thus, 45% of the population decline caused by a birthrate of 1.5 over 20 more years can be attributed to the effect of the increasing age of childbearing women on birth rates. In general, we find that each decade of fertility at current levels leads to declines in ultimate population size of 25 to 40 million, with the contribution of timing remaining around 40% or more in all cases (see table). We arrive at the same conclusion when we assume that, instead of remaining constant, adjusted fertility continues to fall (Frejka & Calot 2001)[4]. The effect caused by increasing age of childbearing clearly deserves attention not just in adjustments to fertility rates (Ryder 1964; Kohler & Philipov 2001), but also when considering determinants of the future size and age structure of Europe's population.

Aging and Delayed Childbearing

Continued increases in the mean age of childbearing will also have significant effects on the age distribution within the population. In the scenario simulating an immediate halt to the delay in childbearing, the "support ratio" declines from about four working-age persons (ages 15 to 64) per elderly person (age 65+) to considerably less than three for most of

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[3] The average tempo effect for 10 EU countries with available data was estimated at about –0.33 for the period 1990 to 1997. Published data are insufficient to reliably estimate the tempo effect for additional EU countries or more recent years (see supporting online material).

[4] Trends in countries with a variety of fertility patterns suggest that the quantum of fertility may decline in the future (see supporting online material).

Table 1. Negative momentum: effect of periods of low fertility on population decline in Europe. The scenarios assume fertility (birthrate) remains constant at 1.5 (continued delay case) or at 1.8 (no further delay case) for the number of years noted in the first column before instantly rising to replacement level. TFR, total fertility rate.

Effect of low fertility on population in Europe

	Population decline by 2100		Contribution of delay	
Period of low fertility (years)	Continued delay (TFR 1.5) (millions)	No further delay (TFR 1.8) (millions)	(millions)	(%)
0	15	15	0	0
10	55	34	22	39
20	88	49	39	45
30	118	63	55	46
40	144	77	67	46

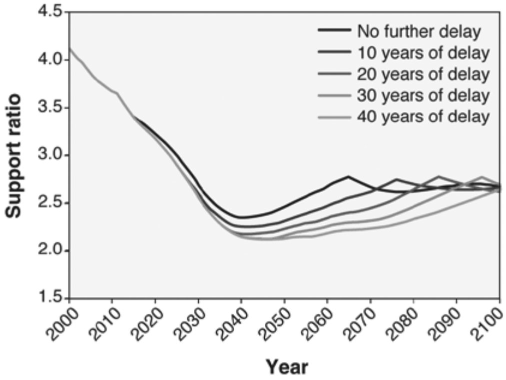

Figure 2. Effect of further delays in childbearing on aging in the EU member states.

the remainder of the century (see Figure 2), if we assume 0 net migration and no changes in mortality. If the delay in childbearing continued with no change in adjusted fertility, the support ratio would further decline to almost 2, nearly doubling the demographic dependence burden as compared with the present. Twenty years of continued increases in the mean age of childbearing imply an additional decline in the support ratio of about 0.5 workers per elderly person by 2065, the year when the difference is most pronounced. The cumulative effects are substantial. Looked at from the perspective of the working-age population, continued delay of 10 to 40 years will imply that an additional 500 to 1500 million person- years of workers would be needed to support the elderly population over the rest of the century, as compared with a no-delay scenario.

Policy Implications

Over the coming decades, the decisive shift to an older age structure in Europe[5] will challenge social security and health systems, may hinder productivity gains, and could

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[5] Aging is also a concern in the United States, although because of higher fertility and higher immigration, aging of the population is anticipated to be less severe. In Central and Eastern Europe, it is more extreme because of lower fertility and no migration gains.

affect global competitiveness and economic growth. It could also strain relations among generations, particularly between those who are on the contributing and receiving ends of public transfer programs. It may also diminish social cohesion, particularly if increasing labor demand leads to substantial immigration from other cultures. Although population aging is the main focus of population-related social, economic, and political concerns in Europe, there is also a deeply rooted fear of population decline (Teitelbaum & Winter 1985) associated with a possible weakening of national identity and loss of international political and economic standing. Policy discussions have primarily focused on adjusting to given demographic trends, by making structural adjustments to pension systems, labor markets, and health and fiscal systems With already very high tax rates, however, there is a limit to how much governments can squeeze out of a shrinking labor force. Hence, discussions are beginning to turn to policies that could influence demographic trends themselves. Because substantial increases in immigration remain politically unpopular, fertility may increasingly be considered as a policy variable (National Research Council 2000). Childbearing could come to be considered a “social act” (Preston 1986) rather than a purely private decision.

In 1976, a set of policies was enacted in East Germany that included much improved child-care facilities, financial benefits, and government-supported housing if a woman became pregnant. As a consequence, period fertility in East Germany, which had declined almost in parallel with West Germany, increased from 1.5 to 1.9 (Büttner & Lutz 1990). The mean age of childbearing stayed below 25 years, while it increased to more than 28 years in the West. In contemporary Western Europe, however, there is pronounced public resistance to explicitly pronatalist policies. This is partly because of infamous birth promotion programs in past fascist regimes and partly because births are often viewed as an obstacle for women pursuing careers and therefore not something the government should promote as an end in itself. Family policies in Europe today are based instead on an equal-opportunities rationale and aim to help women combine child rearing with employment. Such policies seem to have had a small, if any, effect on period fertility (Gauthier & Hatzius 1997).

Policies that aim to affect the timing of births rather than family size may be more acceptable. Such policies would have to address some of the prime reasons for continued childbearing delay, including inflexible higher education systems, youth unemployment, housing markets, and especially career patterns built around traditional male life-course models. Revamping the conventional sequence of life course transitions can also help solve conflicts between work and family (Williams 1999). Health benefits may provide an additional rationale. A continued delay in childbearing has not only led to burgeoning numbers of infertility treatments but also to increasing medical concerns about health risks for mother and child associated with late pregnancies.

Halting the trend toward higher mean ages of childbearing would significantly moderate population aging and decline in Europe. Changes in the timing of births have been pointed out as a possible avenue for slowing population growth in developing countries, in that case by encouraging delays in childbearing (Bongaarts 1994). Here, we are suggesting the reverse: that discouraging further delays in childbearing could help confront the population-related challenge faced by Europe.

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Supplementary Information for "Europe's Population at a Turning Point"[1]

Wolfgang Lutz, Brian C. O'Neill and Sergei Scherbov

Methodology and Data Sources

Description of data sources. This analysis is carried out at the level of the European Union with its current 15 member states. The starting population for the year 2000 by sex and single year of age has been derived from the database of the European Demographic Observatory (ODE) through personal communication with Alain Confesson. These data also include fertility rates by single year of age and mortality rates by sex and single year of age. The ODE database is derived from basic data provided by European statistical offices as part of an international framework for data collection.

Projection methods and assumptions. The alternative population projections were carried out using standard cohort component population projection methods using software developed by the authors. Since this analysis aims at isolating the impacts of alternative fertility assumptions, in all scenarios only the fertility component was modified as described in Table 1, while we assumed that mortality stayed constant at life expectancies of 81.5 years for women and 75.5 years for men. We also assumed a closed population without migration.

Sensitivity to Assumptions on Future Quantum of Period Fertility

Simulations presented in the main text are based on a hypothetical reference scenario in which it is assumed that the adjusted fertility – also called the quantum of period fertility – remains constant in the future at its current level of about 1.8. This simple scenario facilitates analysis of the implications of continued delays in childbearing for future population size and structure. However there are two aspects of our simulations to which results may be sensitive: the assumed magnitude of the tempo effect, and the possibility that the quantum of fertility may decline in the future.

Declines in cohort fertility in recent decades suggest that the quantum of fertility could decline over the next few decades. To investigate the robustness of our conclusions regarding the importance of tempo effects to alternative assumptions about the quantum of fertility, we repeated our calculations for a reference scenario in which the quantum is assumed to decline from 1.8 in 2000 to 1.5 in 2020, a decline of 0.15 per decade which is in the upper range of recent experience in many European countries.

Results show that our main conclusions remain unchanged under this alternative scenario. Because period fertility is lower in these simulations than in the analogous scenarios presented in the main text, future population size is smaller and age structure is older. Figure 1 demonstrates that continued delays in childbearing, if one assumes declining quantum, contribute substantially to the generation of negative momentum by continued low fertility. For example, 20 years of further delay in childbearing is responsible for 37% of the population decline between 2000 and 2100 (the analogous result for the constant quantum reference scenario in the main text is 45%). This result assumes, as in the calculations in the main text, that the tempo effect is constant at 0.3 children per woman. Figure 2 shows that childbearing delays also contribute substantially to changes in the

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[1] published online on the website of *Science*

support ratio. Twenty years of postponement of childbearing implies an additional decline in the support ratio of about 0.3 in 2065, the year when the difference is most pronounced. If delay continues for 40 years, the additional decline in the support ratio is 0.5.

We also tested the robustness of our conclusions to the assumed magnitude of the tempo effect. We repeated our calculations assuming that the tempo effect remains constant at 0.2 births per woman, rather than 0.3 births per woman as assumed in the simulations reported in the main text. As reported in footnote 8 of the main text, the population-weighted average tempo effect based on 10 individual country calculations reported in Bongaarts (8, main text) is 0.33, for the period 1990-1997. Data are insufficient to estimate the tempo effect for the additional 5 EU countries. It is plausible that the inclusion of these countries, and of extending the period over more recent years, could produce a somewhat lower estimate of the average tempo effect in the EU over the past decade, since the increase in the mean age of childbearing is generally smaller over the past few years and in the countries which lack detailed fertility data. Since a precise estimate of the tempo effect is not possible, we use 0.2 as a hypothetical scenario to test sensitivity. Our results show that outcomes change roughly in proportion to the change in the assumed tempo effect. That is, reducing the tempo effect by a third (from 0.3 to 0.2) reduces the contribution of delay to population decline, as reported in Table 1 of the main text, by about a third (e.g., from 45% to 30% in the case of 20 years of further delay). Likewise, the implications of delay for the dependency burden is reduced by a third as well.

Other scenarios, outside the scope of our analysis, are possible as well.

Childbearing delays could be reversed rather than simply halting, causing the mean age of childbearing to decline. In addition, changes in the tempo of fertility could interact with the quantum. For example, it has been suggested that postponement of births can induce declines in quantum. We suggest that the reverse may be true as well: if births begin to shift to younger rather than older ages, this may induce an increase in the quantum. In this way the effect of policies influencing the tempo of fertility may be magnified through their indirect effects on the quantum.

Table S1. Period fertility assumptions for all scenarios in main text and supplementary material. Fertility is interpolated linearly between values shown in the table, and remains constant beyond 2050. Scenarios 1, 9, and 13 appear in Fig. 1; scenarios 1 and 8-15 are used to construct Table 1; scenarios 2 and 4-7 appear in Fig. 2; scenarios 1, 9, 13, 20 and 21 appear in Fig. S1; scenarios 2, 16, 17, and 19 appear in Fig. S2.

Scenario Nr.	*Name*	**2000**	**2001**	**2010**	**2011**	**2020**	**2021**	**2030**	**2031**	**2040**	**2041**	**2050**
1	Instant replacement level	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
2	Constant quantum, no further delay	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
3	Constant quantum, continued delay	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
4	Constant quantum, 10 years further delay	1.5	1.5	1.5	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
5	Constant quantum, 20 years further delay	1.5	1.5	1.5	1.5	1.5	1.8	1.8	1.8	1.8	1.8	1.8
6	Constant quantum, 30 years further delay	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.8	1.8	1.8	1.8
7	Constant quantum, 40 years further delay	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.8	1.8
8	Scenario 3 + replacement level in 2011	1.5	1.5	1.5	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
9	Scenario 3 + replacement level in 2021	1.5	1.5	1.5	1.5	1.5	2.06	2.06	2.06	2.06	2.06	2.06
10	Scenario 3 + replacement level in 2031	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.06	2.06	2.06	2.06
11	Scenario 3 + replacement level in 2041	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.06	2.06
12	Scenario 2 + replacement level in 2011	1.8	1.8	1.8	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
13	Scenario 2 + replacement level in 2021	1.8	1.8	1.8	1.8	1.8	2.06	2.06	2.06	2.06	2.06	2.06
14	Scenario 2 + replacement level in 2031	1.8	1.8	1.8	1.8	1.8	1.8	1.8	2.06	2.06	2.06	2.06
15	Scenario 2 + replacement level in 2041	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	2.06	2.06
16	Declining quantum, no further delay	1.8				1.5	1.5	1.5	1.5	1.5	1.5	1.5
17	Declining quantum, 20 years further delay	1.5				1.2	1.5	1.5	1.5	1.5	1.5	1.5
18	Declining quantum, 30 years further delay	1.5	**Interpolated**			1.2	1.2	1.2	1.5	1.5	1.5	1.5
19	Declining quantum, 40 years further delay	1.5				1.2	1.2	1.2	1.2	1.2	1.5	1.5
20	Scenario 17 + replacement level in 2021	1.5				1.2	2.06	2.06	2.06	2.06	2.06	2.06
21	Scenario 16 + replacement level in 2021	1.8				1.5	2.06	2.06	2.06	2.06	2.06	2.06

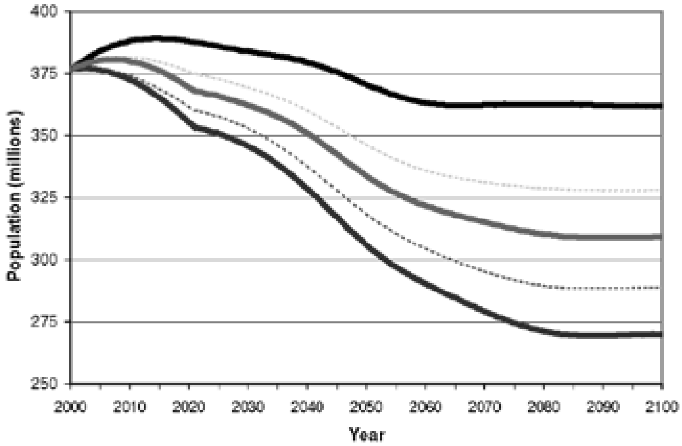

Figure S1. Effect of 20 more years of low fertility on population size, if one assumes declining quantum of period fertility. Population of the EU-15 if one assumes fertility immediately increases to replacement level and remains constant thereafter (black line), and if one assumes fertility declines linearly from 1.5 to 1.2 (dark green line) or 1.8 to 1.5 (bright green line) in 2020 when it rises to replacement level. For comparison, dotted pink and red lines show results from Fig. 1 in the main text, if one assumes constant quantum of period fertility [fertility remains at 1.5 (red line) or 1.8 (pink line) until 2020 when it rises to replacement level]. Mortality is held constant and migration is set to zero in all cases.

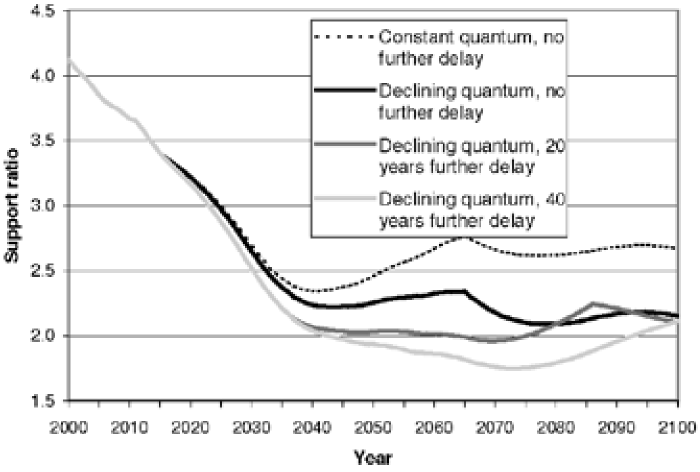

Figure S2. Effect of further delays in childbearing on aging, if one assumes declining quantum of period fertility. Support ratio in the EU-15, if one assumes zero to four decades of further delay, with mortality held constant and no migration. For comparison, the dotted black line shows results from Fig. 2 in the main text and is based on the assumptions of constant quantum of period fertility and no further delay in childbearing.

Population Futures for Europe: An Analysis of Alternative Scenarios[1]

Douglas Wolf, Babette Wils, Wolfgang Lutz and Sergei Scherbov

1. Introduction

Population projections are an important product of demographic analysis, for several obvious reasons. Whet her in planned or market economies, governmental officials, personnel directors, plant managers, educators, military leaders, and others all find it useful to "know" how many people there will be, and what the characteristics (age, sex, education levels, family status, and so on) of the population will be, in years to come.

Of particular concern is the delicate relationship between people and their physical and natural environments – as the numbers of people grow, so does the usage of resources and space, as well as the accumulation of by-products – often in the form of wastes – of that resource use. It is, in fact, a concern with future of population growth and its potential environmental consequences which motivates the present paper, which is part of a larger effort undertaken at IIASA in recent years, one focusing upon the future of Europe. Here we examine several alternative population-growth scenarios for Europe over the coming decades; we do not comment upon the environmental consequences of the alternative scenarios, but rather present them to the larger community of futures analysts.

The components of population dynamics are straightforward and few in number: births, deaths, and net migration. This is true whether we contemplate the regional, national, or global level, except that at the global level (under current transportation technology) net migration must be zero. If we add to these three components an additional category of information, namely the size and structure (according to age and sex) of an initial population, it is a straightforward exercise to compute a projection of the future population in any year. An overview of what has become a standard tool for population projection can be found in chapter 11 of Keyfitz (1982).

Despite the standardization of methods for population projection, projections remain a hazardous and error-ridden undertaking, and do so for the simple reason that it is impossible to correctly guess the future path of fertility, mortality, and net migration. It is possible to make rather good guesses – especially for the near-term future and for components such as mortality rates, which have tended to show fairly regular trends over time. In recent yea.rs demographers have devoted some attention to the analysis of ex post errors in population projections, and have identified some factors associated with the relative size of the error; see for example Keyfitz (1982), Stoto (1983) and Land (1986). But correct guesses remain in the realm of the impossible.

In virtually all population projections it is the analyst's goal to calculate as closely as possible what time will reveal to be the actual path of the population. And, if not, this should be the goal, since the users of projections typically treat the numbers as answers to the question "what will happen?" Here, we attempt to answer a very different question, namely, "what *might* happen?" Our object is to anticipate what might be major demographic "surprises" of the coming decades, and then calculate what the population consequences of such surprises would be. Our attitude is that even unlikely surprises may nonetheless

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materialize, and that we should therefore contemplate a broad range of possible (if unlikely) alternative scenarios. There are of course an infinity of such alternatives; in what follows we confine ourselves to an exposition of five rather extreme alternative scenarios, representing major departures from recent mortality, fertility, and migration experience in Europe. For reasons of data availability, elaborated later, we omit from our analysis the European parts of the Soviet Union.

The outline of the paper is as follows: in the next section, we provide a context for the scenario analysis by describing the main demographic trends of postwar Europe; we consider mortality, fertility, and migration in turn. Section 3 describes our projection methodology, while Section 4 presents what might be labeled the "conventional wisdom" regarding Europe's future population. Section 5 presents our main findings, describing the assumptions underlying the alternative scenarios and presenting the corresponding calculations. A brief summary and discussion concludes the paper.

2 Demographic Trends in Postwar Europe

In order to set the stage for our scenario analysis, we present a brief survey of demographic developments in Europe, focusing upon the post-World War II period. The demo graphic trends and patterns exhibited during this period are important for two reasons: first, they have much to do with the composition of the present population of Europe, which in turn is the starting point for any population projection; and, second, it is only in the context of recent trends that the analyst can develop plausible assumptions regarding the future paths of the demographic parameters which serve as inputs into the projection.

In this section, we present an overview of mortality, fertility, and migration patterns.

Mortality. Age-specific mortality rates – for example, the number of deaths to men (or women) in a given age-group during the year, divided by the mid-year population in the given age and sex category – display a distinctive pattern. The pattern begins with rates which are somewhat high during the first year of life, but which drop off rapidly and remain low throughout childhood and into early adulthood , and then climb slowly, and later (around ages 50 and onward) progressively more rapidly. It is common to summarize mortality rates in a single, simple index, the expectation of life at birth. This is the average number of years that people would live if they experienced the given age-pattern of mortality rates throughout their lifetime.

Figure 1 displays life expectancies by sex for Europe, with actual data for 1950-1980, and the assumed path of life expectancy for 1985-2020. These data are used in the United Nations medium-variant population projection, discussed in more detail later. The two key features of Figure 1 are, first, the fact that women on average live longer than men and, second, the fact that the female-male differential has been widening. Moreover, the UN projections assume that the female-male differential will continue to widen throughout the projection period. According to the UN assumption, female life expectancy will be around 80 years by the year 2020, a level which has already been surpassed in Japan.

The sex-specific curves shown in Figure 1 mask considerable underlying diversity. One example of diversity is illustrated in Figure 2, which shows regional patterns of male life expectancy in Europe. According to this figure, in 1950 male life expectancy in Northern and Western Europe was several years greater than in Southern and Eastern Europe. But by 1970 male life expectancy in the southern region had risen to that of the western region; in the meantime male life expectancy stopped growing in Eastern Europe. In fact, detailed

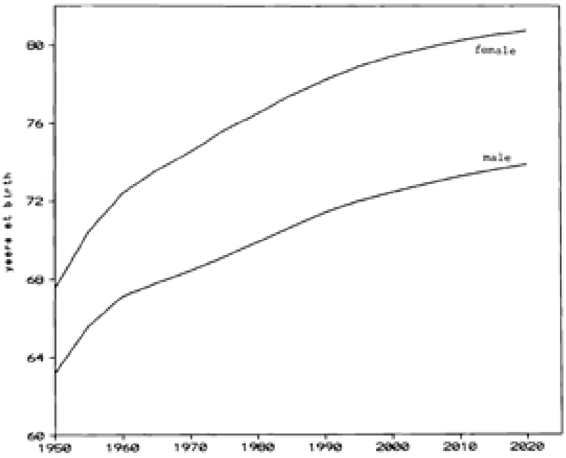

Figure 1. Life expectancy in Europe, by sex.

analyses of country data have shown that death rates of working-age men have actually declined in some countries; these declines would have translated into a *reduction* in overall life expectancy, had they not been offset by improvements in infant and childhood mortality (see, for Hungary, Carlson & Watson 1988, and for Poland, Okolski 1985). The corresponding region-specific curves for women (not shown) reveal a pattern which is similar to that found in Figure 2, though not so exaggerated.

While the age-pattern of mortality described before has remained fairly stable (except when upset by exogenous factors such as war), future mortality pat terns could be quite different. It has been argued (especially by Fries 1980) that future developments in adult mortality will cause the life-table – that is, the pattern of survivorship to specified ages – to become essentially *rectangular*. That is, there will be a tendency for deaths to become

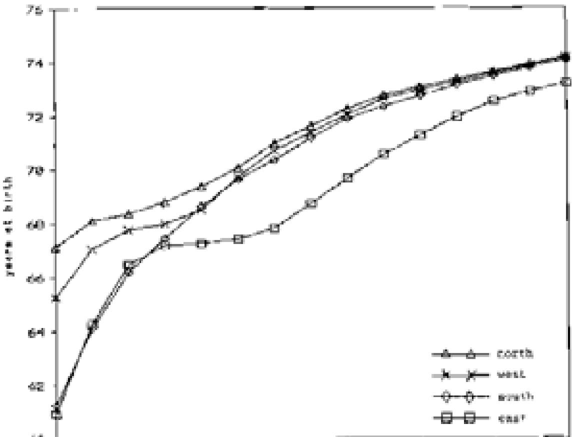

Figure 2. Male life expectancy in Europe, by region.

concentrated at a theoretical maximum life span (of around 85 years), at which age most people will die. It has been argued that this progress is-and will be – due to improved personal health habits in combination with better medical care. Others, however, noting recent scientific advances in health care and medical research, have speculated that large and dramatic breakthroughs in mortality may emerge, raising the prospect of a "Methuselah society" in which large numbers of people live to unprecedently old ages (see, for example, Vaupel & Gowan 1985).

In one of our scenarios we postulate developments in old-age mortality which com bine elements of both the "fixed life-span H and the "Methuselah" viewpoints: we suppose that mortality after age 60 will drop dramatically and rapidly, in a way suggestive of sudden technological breakthroughs, but that the span of human life will remain bounded above (at age 100).

Another recent development in mortality, still too early to be reflected in the published (and highly aggregated) data displayed in Figures 1-2, is the AIDS epidemic. The extent and ultimate consequences of AIDS remain largely unknown. In consequence, the literature contains a broad range of estimates and prognoses regarding the future path of the disease. We have picked from the literature one of many possible sets of assumptions regarding the dynamics of AIDS, and include this as one of our scenarios.

Fertility. During the last century all European populations experienced a fundamental change in their reproductive pattern. Demographers call this change the *secular fertility transition*, which together with a substantial mortality decline constitutes the *demographic transition*. This describes the fundamental change from a fertility pattern in which, for married couples, the number of children was virtually uncontrolled to a situation where couples more or less consciously determine the family size they want. Under the earlier regime, for married women the number of children was essentially a function of biological factors. Now, conscious planning together with the availability of efficient contraceptive methods makes personal family size desires the crucial variable.

The qualitative transition from "natural" to "controlled" fertility, which in most European populations took place early in this century, resulted as well in a significant change in the average number of children born to women over the course of their reproductive life. The total fertility rate (TFR) is a measure of the mean number of children born per woman as implied by observed age-specific period fertility rates. In most Western European countries the TFR declined from about 4-5 children per woman in 1900 to 2-3 children in the 1930s. In Southern and Eastern Europe the fertility transition took place somewhat later.

Figure 3 gives the trends in age-specific fertility rates for Finland from 1776 to 1984. In this figure one can clearly see the pre-modern fertility fluctuations at a high level, followed by a steep secular decline lasting until about 1940.

In most European countries the economic depression of the 1920s and 1930s was accompanied by very low fertility levels. The war which followed lead to considerable heterogeneity among the countries and particularly strong annual fluctuations in fertility. After the end of World War II all European countries showed an upsurge in the number of children, known as the postwar "baby boom". This phenomenon of strongly increasing fertility levels in almost every country was quite unexpected by demographers. In many countries we can identify two maxima, one right after the war and one in the early 1960s. The two examples given here (Figures 3 and 4) show two extremes in the timing of the baby

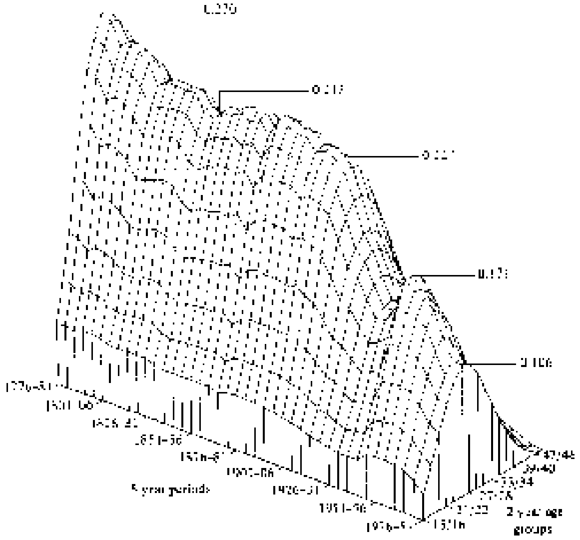

Figure 3. Age-specific fertility rates in Finland, 1776-1981.

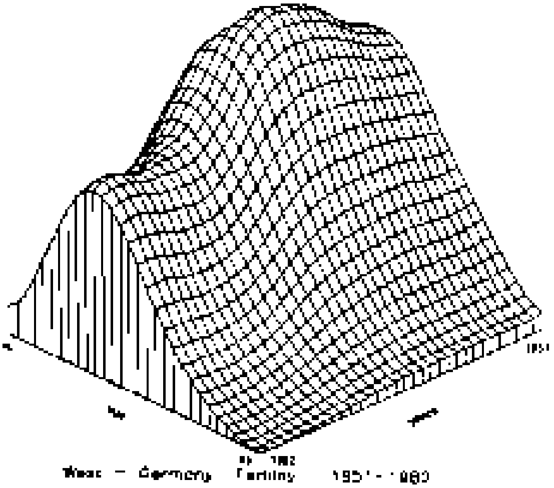

Figure 4. Fertility trends for the German Federal Republic.

boom.[2] In Finland the highest fertility levels were observed in 1947-1948, when the TFR reached almost 3.5 (equal to the level of 1916-1918) followed by a constant decline until recently. In the German Federal Republic fertility peaked in 1964 with a TFR of slightly above 2.5; for the 12 years from 1957 to 1969 it was at a level of above 2.2. After 1969 fertility in Western Germany had declined to levels somewhat under 1.4, where it now appears to have stabilized.

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[2] The sources for Figures 3 and 4 are Lutz (1987) and Lutz and Yashin (1987), respectively.

What are the determinants of these trends in national fertility, and what can we know about future trends? Without going into the very extensive literature on fertility determinants, we will mention here only a few simple explanations. The secular fertility transition from uncontrolled to controlled fertility was largely accompanied by the transition from an agricultural rural society to a modern industrial society; children who represented additional help on the farm meant additional cost in an industrialized society. But equally important to these economic changes were probably cultural changes: people started to become more highly educated, to plan their life, and to change emphasis from the quantity to the quality of children. The postwar baby boom is now understood by demographers as being to a great extent a timing phenomenon. Women who had delayed births during the war had them later. Concurrently, younger women started their child bearing sooner than had previous cohorts. This compression of childbearing activity into a few years became the baby boom. The fact that during this period marriage in Western Europe had become almost universal, and the mean age at marriage had declined, also contributed significantly to the baby boom.

More recently marriage has become less popular and also the number of children born within marriage has declined, on average, due to changes in the value pattern and structure of our modern society. The changing role of women in the family, in society, and in economic activity seems to be closely associated with this recent decline; but so also is a cultural shift from orientation towards the family to individualism, an observation sometimes called the "second demographic transition" (Van de Kaa 1987).

It is usually assumed that the marital fertility transition early in this century was an irreversible process; the irreversibility of the more recent changes remains unknown. For this reason we include two different fertility scenarios in our study, one assuming further steep fertility declines, and the other assuming the occurrence of another "baby boom".

Immigration. The pattern of immigration to Europe from year to year since World War II has not been uniform. After a century of being a large net exporter of people – to the New World – Europe gradually became a net importer of people since World War II. This shift occurred in different ways and at different times for various nations. In general, net immigration became positive earlier in West and North Europe. Partly, this was due to a large influx of people from South Europe in the 1950s and 1960s.

By the 1970s, perhaps as economic differences in Europe decreased, South European migration decreased. A large influx of workers and dependents from outside Europe continued. Nations with a colonial past experienced a large influx from their ex-colonies – for example from Pakistan, India, and the West Indies to Great Britain; from the Maghreb and West Africa to France; and from Indonesia and Surinam to the Netherlands. Otherwise, large groups came to Europe from the South and West Mediterranean nations – notably from Morocco and Turkey. This second group initially formed the new immigrant category, "guest worker", meant to work in the "host country" for a few years and then return home. But many did not return, and instead brought their dependents after a few years, to remain permanently.

Presently, the influx of immigrants has decreased, as economic and social problems in Europe have led to an increasingly parsiminous distribution of new work permits. In those countries for which we had data, it appears that ongoing immigration consists mainly of dependents or non-workers. Presumably, unless new workers arrive, this immigration will also gradually dwindle. A new, presently small, group of immigrants are refugees. That the decreased immigration cannot be caused by decreased pressure in sending countries (as

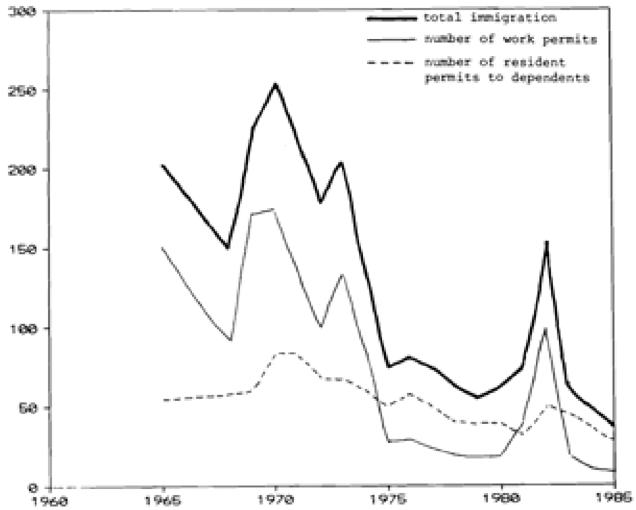

Figure 5. Immigration into France 1965-1985.
Source: Annuaires Statistiques.

was the case for past pan-European immigration, and probably for South Europe in the seventies) is rather obvious. The pressure from developing countries to allow immigrants into Europe is more likely to increase than otherwise. As a concrete illustration of the historical trends reviewed here, Figure 5 is presented which shows the patterns of migration France from 1960 to 1984.

The absolute number of immigrants in the past decades appears large. Net migration to EEC countries was a bit under 500,000 annually from 1960 to 1976 (Eurostat 1977). But relative to the total population net immigration has generally been small. Available statistics indicate that during the peak years migration accounts for annual population increase of about 0.1 percent. One much higher figure – but still less than 0.5 percent – reflects a unique situation in the Netherlands when a mass exodus occurred from the colony Surinam the year before its independence. Moreover, in most of the period in question, net migration was much lower, equaling about 0.025-0.05 percent annual population increase.

Once arrived, the immigrant population can cause further increase due to natural growth. Espenshade (1987) and others note that the immigrant population often accounts for nearly all of a nation's natural growth. There are two reasons for this. The first is the age structure of the immigrant population. Immigrants are typically concentrated in the childbearing but low-mortality age group between 20 and 45; an example, illustrating the case of the German Democratic Republic in 1976, is given in Figure 6. Thus immigrants contribute substantially to fertility while contributing very little to mortality, and this alone will cause an immigrant population to grow relative to the native population.

The second reason is higher fertility in the immigrant than in the native population. While data on immigrant fertility in Europe are difficult to obtain, available examples – such as a TFR of 3.009 for foreign women in the Netherlands, compared to only 1.437 for Dutch women, both in 1984 (Frey & Lubinski 1987) – indicate fertility levels which are considerably above that of the host population. Yet these high immigrant fertility levels tend to decline over time, becoming increasingly like those of the native population. In our scenario dealing

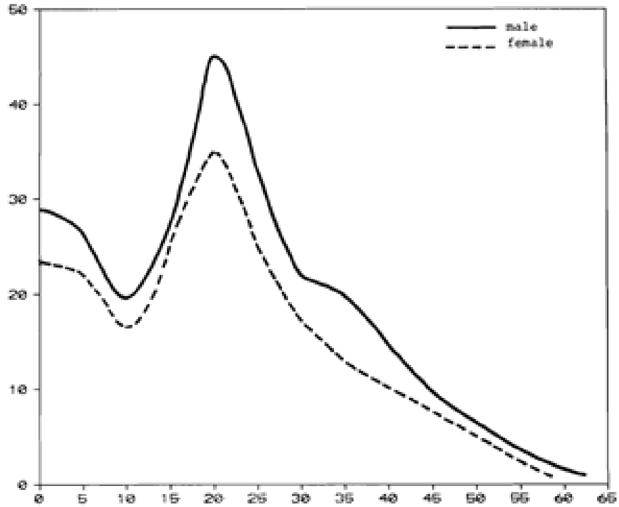

Figure 6. Age curve for migrants into the German Federal Republic in 1976.

with immigration, we assume that fertility differences between the immigrant and the host population vanish after 25 years.

3 Methods

As noted m the introduction, the methods of population projection are highly developed and fairly standardized. Our calculations use the usual components approach, in which the initial population is represented in terms of counts by 5-year age groups. The projection is carried out in 5-year calendar time units. In each time period, the proportion of each age group surviving until the next period is determined by the application of survival probabilities, which are in turn a function of age-specific mortality rates. Similarly , the number of newly-born people is determined by applying the appropriate age-specific fertility rates to women in the age groups for which childbearing is possible (generally, and, in particular, in our calculations, ages 15-49). The survivorship until the end of the 5-year period of babies born during the period must also be determined. And, finally, net immigrants in each age-sex group must be added to the population.

Our calculations were obtained using the interactive microcomputer program called DIALOG, a full description of which can be found in Scherbov and Grechucha (1988). The DIALOG program is especially well-suited to the problem at hand, the examination of alternative scenarios. As noted above, the projection mathematics are based upon birth and death rates which are specific to each 5-year age group; the resulting schedule of rates is frequently called an “age-pattern” of mortality or fertility. Each pattern of rates can be summarized with a single index, such as the TFR for fertility, or life expectancy at birth, for mortality. Except as noted later, we specified our scenarios as trends in the respective indices, rather than in their individual age-specific components. The DIALOG program translates these assumptions into new patterns of birth or death rates by scaling up or down, as appropriate, the respective array of rates until the associated index agrees with the assumptions of the alternative scenario.

4 Europe’s Future Population: The Conventional Wisdom

We have chosen to present, as a representative of the “conventional wisdom” regarding Europe’s future population, the projections produced biannually by the United Nations’ Population Division; we focus in particular on the 1986 edition of these projections (United Nations 1986). Our choice is partly dictated by convenience, since the UN projections are available in machine-read able form and therefore very useful for analytic purposes. Moreover, the projections a.re presented not only by individual country but by region and continent, including all of Europe (excluding the part found in the USSR) as well as four subregions (North, East, South, and West Europe).

The UN produces three variant forms of its projections, a. medium as well as low and high variants. These differ only in their assumption regarding fertility trends. We focus throughout on the medium variant, since, in the words of Keyfitz, ”...[t]he interpretation of middle-variant projections as forecasts has been nearly universal among users” (1982, p.196).

The essential ingredients of the UN projections a.re the initial population, and the assumed path of fertility and mortality rates. The mortality assumptions, summarized in the form of life expectancy at birth, were shown in Figure 1. The assumption regarding mortality is that life expectancy will continue to increase, by about 4 years, reaching 73.87 for men and 81.74 for women in 2020.

The remaining information is presented in Figures 7 and 8: Figure 7 depicts the starting population, in the form of an age-pyramid for 1980, while Figure 8 is a graph of the medium-variant assumptions regarding fertility (the TFR). Note that the UN projection embodies the assumption that fertility, which has been falling steadily and rather steeply since 1960, will in the immediate future reverse its downward trend, rising slowly from 1.825 (in 1980) to 2.045 – almost the replacement level – by 2020.

We reproduced the UN medium-variant population projection for Europe using the DIALOG program, the results of which are shown in Figure 9. Although the UN’s own projections go only until 2025, we continued the projection to 2050, using the assumption

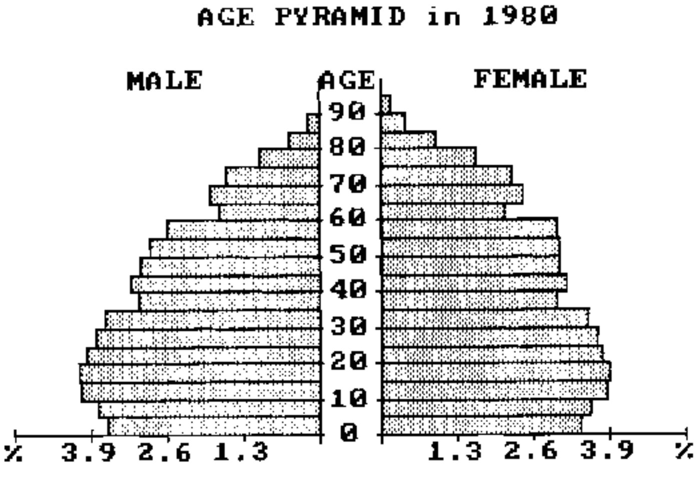

Figure 7. Age pyramid for Europe: 1980.

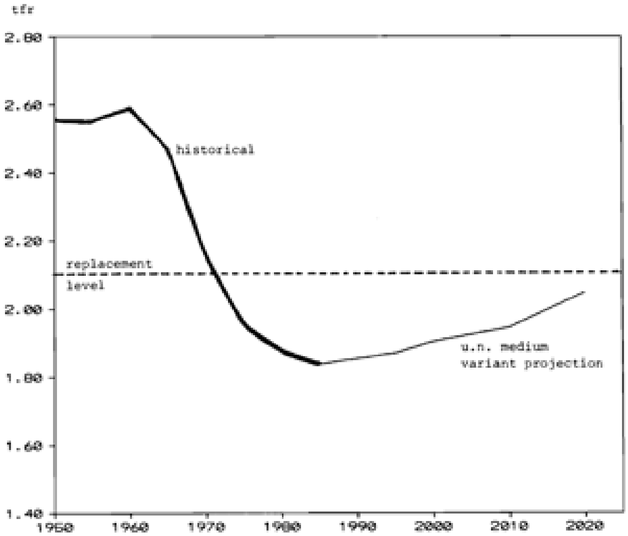

Figure 8. Total fertility rate for Europe: 1950-2020.

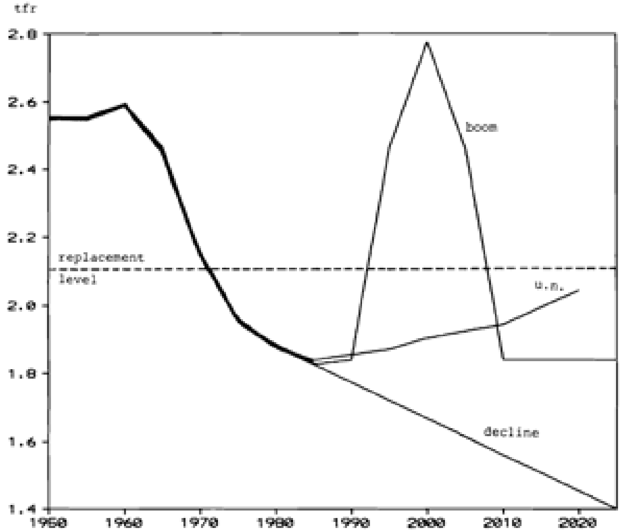

Figure 9. Projected European population, total and by age-group: UN medium-variant projection.

of no change in fertility or mortality after 2025. According to this projection, Europe's total population will rise gradually until 2030, at which time it will reach 526 million, which represents a 8.6 percent increase (or, a 0.16 percent annual growth rate) from the 1985 base of 485 million (recall that the European part of the Soviet Union is excluded from our analysis). Figure 9 also plots three broad age groups – those 0-19, those 20-64, and those 65 and older. The number of young people is projected to remain almost constant, while the working-age generation shrinks, and the elderly population grows dramatically, both in absolute numbers and in relative size.

Although we present the UN medium-variant projection as a representative of the “conventional wisdom”, we must point out that the figures are not universally or uncritically accepted by students of population. The UN’s medium-variant projection has in fact been termed a “bright future” (Macura & Malacic 1987, p.20) mainly in view of its assumptions regarding the future path of fertility. There is no obvious reason to suppose that Europe’s downward trend in fertility, a long-standing trend, will suddenly (and soon) reverse course, returning gradually to the replacement level. As we have already indicated, it is for this reason that we include as one of our illustrative scenarios a continued downward trend in Europe’s TFR.

5 Europe’s Future Population: Some Alternative Scenarios

Assumptions. Our alternative scenarios consider some extreme possibilities for each component of population growth. For fertility, we consider two possibilities, another “baby boom”, larger than that of the postwar years, and (in our opinion, more realistically), a drop of fertility to the low levels currently observed in a few European countries. For mortality, also, we consider two possibilities; the first is a medical breakthrough (which we label, only partly in jest, a “magic drug”) the effect of which is to reduce old age death rates dramatically, and the second is a major epidemic-an extreme AIDS scenario. Finally, we examine the consequences of a major influx of immigrants, on a scale larger than experiences anywhere in Europe in the postwar years.

The specific assumptions underlying each alternative are given below.

1. A new baby boom: the TFR starts to increase from 1.825 in 1990 to 2.776 in 2000, and decreases again to 1.825 by 2010. This would constitute a more dramatic, and more compressed, baby boom than that actually experienced in postwar Europe.
2. Fertility decline: the TFR continues to decline in Europe, to an overall level of 1.4, a level already reached in some West European countries. The assumptions for scenarios (1) and (2) are depicted in Figure 10.
3. A “magic drug” is introduced on the market in 2000 which decreases mortality for those over 60 by 50 percent.
4. A major epidemic: in order to represent a possible AIDS scenario, we note that while the present number of reported cases is about 6000 in Europe, the actual number of infections is assumed to be 40 times higher. It is assumed that the number of infections doubles annually, and that all of those infected die 10 years after infection, until half of the population aged 30-50 dies of AIDS. The other half is assumed to be immune and remains unaffected. These assumptions correspond roughly to the analysis presented by Platt (1987). Note that we apply the assumed mortality increases to both sexes. The mortality assumptions used in scenarios 3 and 4 are shown graphically in Figure 11.
5. A new wave of immigration: our last scenario postulates the occurrence of a turnof-the-century burst of immigration larger than the one experienced in the sixties and seventies. From 1995 to 2004 there are one million immigrants annually. The age and sex structure is roughly historical: 55 percent male and 45 percent female, with age concentrated between 20 and 30. The immigrants’ TFR is initially twice as high as the European rate, then declines gradually to the native level by 2025. Figure 12 shows the

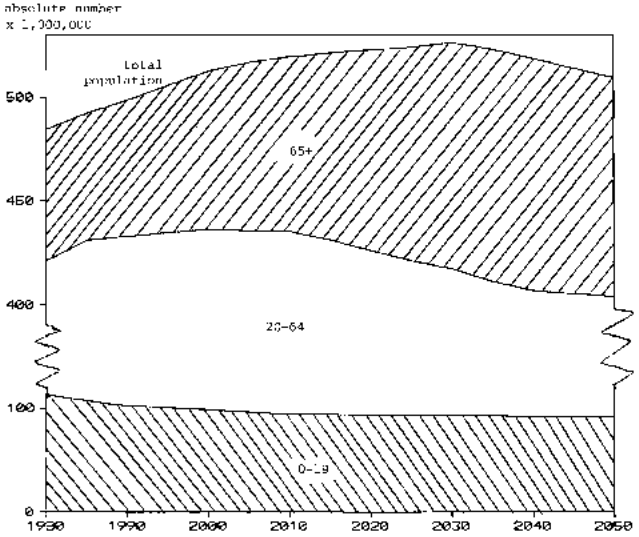

Figure 10. Total fertility rates for alternative scenarios: “baby boom”, fertility decline, and UN medium variant.

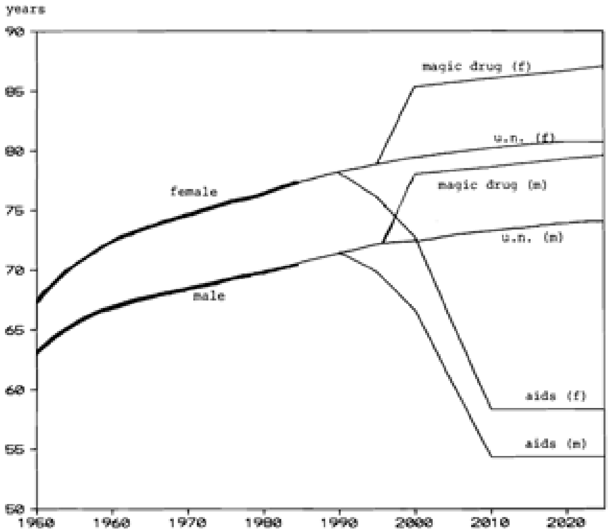

Figure 11. Life expectancy, by sex, for alternative scenarios: “magic drug”, AIDS epidemic, and UN medium variant.

net immigration into the EEC from 1960 to 1976 together with the assumed magnitude of the “new wave” immigration scenario.

The UN assumptions hold for those variables not included in the scenarios. Also, note that each scenario involves only a single set of alternative assumptions. We do not explore the consequences of *combinations* of different assumptions, but these would be, for the

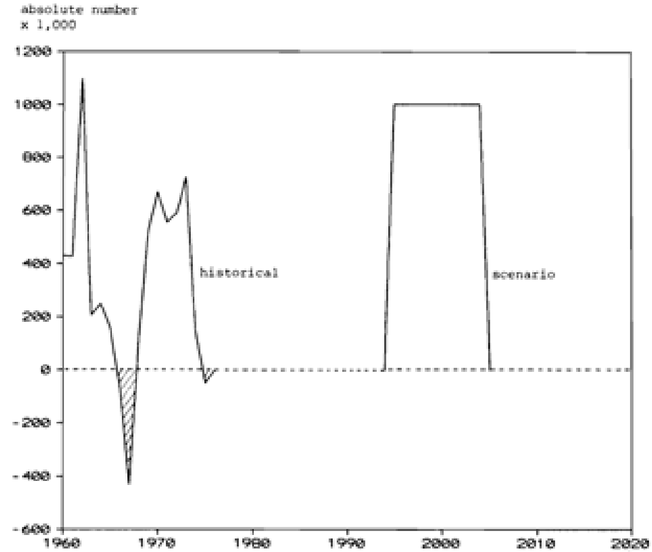

Figure 12. Immigration (in 1000s): 1960-1976 for EEC, and assumed volume for immigration scenario.

most part, additive. Thus the reader can readily determine the population that would result if, for example, both the low-fertility and the high-immigration scenarios were to materialize.

Results. The population paths implied by each of our alternative scenarios is pictured in Figures 13-15. In each, the UN medium-variant projection is also shown for purposes of comparison. In Figure 13, which shows the total population, we see that three of our scenarios – the baby boom, “magic drug” and new wave of immigration – imply more growth than does the UN projection, while the other two – fertility decline and AIDS – imply a sharp reduction in Europe’s population. It is interesting to note that the three growth scenarios are, in effect, scenarios for upward shifts in the conventional-wisdom growth path, followed by population trajectories essentially parallel to the UN projection.

In contrast, the fertility-decline and the AIDS scenarios both imply a sharp departure from recent trends. In both cases, Europe’s population peaks, at somewhat below 520 million, around 2000-2005, after which it shrinks at a rapid rate.

The age-composition of Europe’s future population differs dramatically across alternative scenarios. Information on age structure is shown in Figures 14 and 15. Figure 14 shows the percentage of the population in the 15-64 age group; this is the group from which most of the labor force must be drawn. Under all the scenarios, this percentage will be at or near its peak in 1985-1990, and will decline thereafter. The decline is most precipitous for the “magic drug” scenario, where the percentage below 65 is pushed down by the massive growth of the over-65 population (see Figure 15). The “baby boom” and AIDS scenarios display more fluctuation, and more transitory changes, since in each case the underlying phenomenon occurs during a relatively compressed period of time.

Figure 15, which depicts the percentage of the population 65 and older, for the most part mirrors the curves shown for the working-age population in Figure 14. Both the

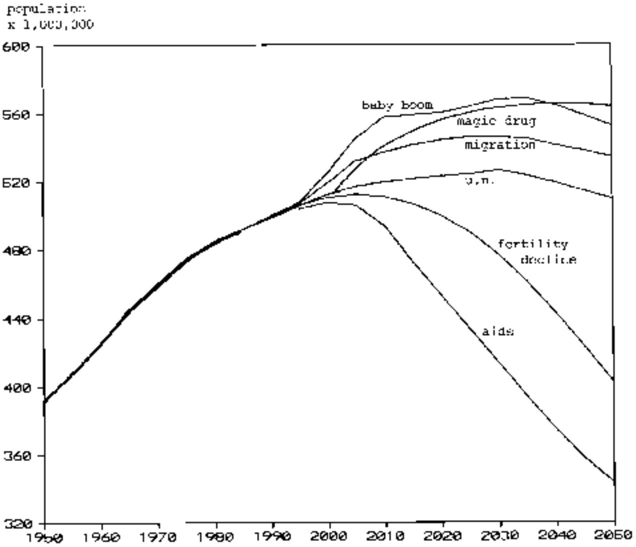

Figure 13. Projected European total population: six alternative scenarios.

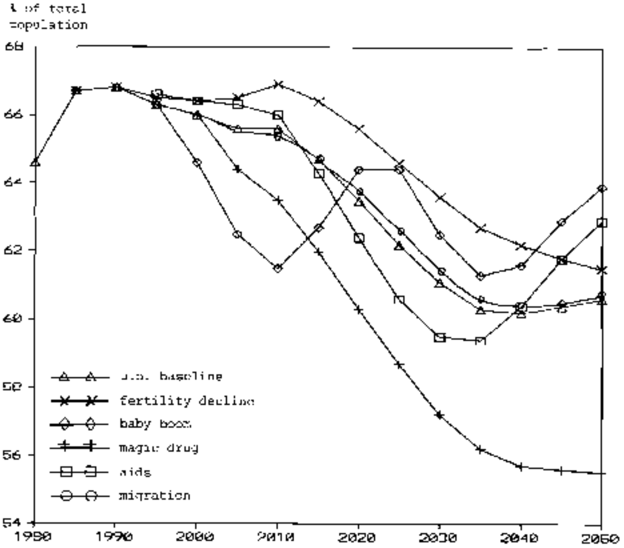

Figure 14. Percentage of projected population aged 15-64: six alternative scenarios.

fertility-decline and the "magic drug" scenarios imply dramatic growth in the percentage of the population elderly; in the first case, the cause is the failure of the population to add sufficient numbers of young people, and in the second case, the cause is a reduced tendency for the older population to die off. Note that even under the conventional-wisdom projection the percentage of the population elderly is expected to rise a lot; our baby-boom and immigration scenarios do little to change this feature, while the magic drug and fertility-

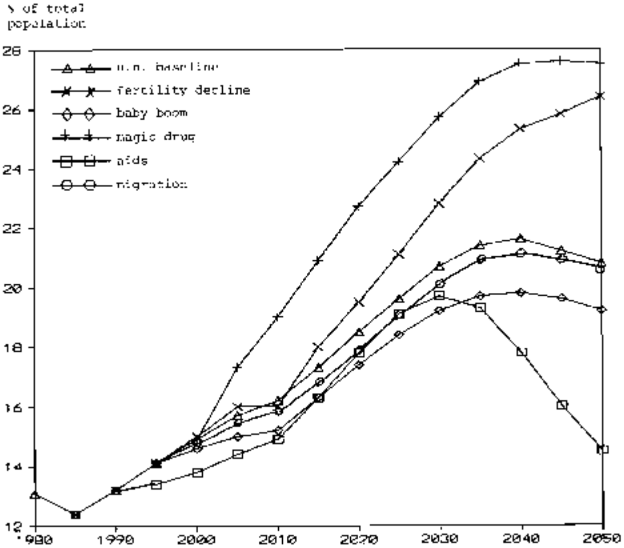

Figure 15. Percentage of projected population aged 65 and over: six alternative scenarios.

decline scenarios merely amplify it. Only under the AIDS scenario does the percentage elderly drop, and this it does during the years when those who died young from the disease would otherwise have entered the over-65 group.

6 Summary and Discussion

This paper has discussed the possible path of Europe's population to the year 2050, employing an alternative-scenario approach. Our objective has been not to guess what the most likely path of population growth will be, but rather to identify a range of possible, albeit extreme or unlikely , paths of population development. We have addressed all of the basic elements of population dynamics: birth rates, death rates, and the net inflow of immigrants. A characteristic of all three elements historically has been the occurrence of unexpected events – "surprises" – especially in the area of fertility. We have no reason to suppose that the future is without surprises, and have tried to anticipate some of them in our various scenarios.

Among the surprises – or reversals of trend – we have contemplated are: an end-of century baby boom of un precedented size; continued decline of fertility to a point at which Europe overall is well below replacement; a dramatic and rapid drop in old-age mortality rates; a worst-case AIDS scenario; and a new wave of immigration. Of these, the fertility-decline and the AIDS scenarios lead to the most dramatic results, in each case implying rapid shrinkage in the size of Europe's population after the year 2000, accompanied by pronounced changes in the age structure of the population. The other scenarios, and particularly the immigration scenario, depart rather little from the medium-variant projections produced by the United Nations.

Even though our scenarios are not meant to represent the actual, or even the likely, future, they can still be instructive about what the future may hold in store. And, equally importantly, the scenario analysis helps to identify what sorts of "surprises" would have large consequences, and what sorts would not. For example, even though we assumed immigration on an unprecedented scale, our high-immigration scenario led to only modest growth in Europe's population, beyond what would be expected on the basis of the conventional-wisdom view. Even a very large baby boom does not lead to an abrupt shift in the population growth path.

What does turn out to make a big difference in Europe's future is the fertilityreduction and the AIDS scenarios. In both cases, precipitous population decline begins to occur early in the next century. Yet we again point out that in our view, the fertilitydecline scenario is more realistic than that assumed in the UN projections: we have merely assumed a continuation of the fertility trends of the last two decades, until all of Europe (on average) reaches a low level of fertility, a level which several countries have al ready reached (or gone below). Moreover, the AIDS scenario that we modeled, while not necessarily the "conventional wisdom", corresponds to assumptions and assertions being made in the existing literature.

Finally, it should be pointed out that whatever the future holds, it will include changes in fertility, mortality, and immigration simultaneously, not singly as in the scenarios we analyzed. As mentioned before, some of the changes would be additive-for example, the immigration results can simply be added to the fertility results, to obtain the population implications of the two assumptions together. Some of the changes, how ever, would not be additive. In particular, if an AIDS epidemic on the scale examined here were to materialize, it is quite possible that fertility rates would drop as well, as people adopted a more cautious attitude towards sexual activity. Our results indicate that such an interaction would only accelerate the implied shrinkage of the population.

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Very Long Range Global Population Scenarios to 2300 and the Implications of Sustained Low Fertility[1]

Stuart Basten, Wolfgang Lutz and Sergei Scherbov

1. Introduction

I don't want a second child. One is enough, and I hope it is a girl. It is very nice to be the only child; you don't need to share or grab things from others. You can have all your parents' attention. My parents have brothers and sisters, but when my grandparents died they quarrelled over the legacy. That was horrible and hurtful. Being the only child, you won't have those problems. 25-year-old Shanghainese expectant mother (Branigan 2009)

The future number of humans on our planet will crucially depend on the future level of human reproduction in different parts of the world, which is uncertain. Depending on whether the global level of fertility is assumed to converge to the current European TFR (~1.5) or those of parts of Southeast Asia or Central America (~2.5), global population will either decline to 2.3-2.9 billion by 2200 or increase to 33-37 billion, if mortality continues to decline. The process of demographic transition has resulted in universal fertility declines (with the global TFR declining from 4.9 in the 1960s to 2.6 currently), with the decline failing to halt at a replacement level of around 2.1 in many countries, as was anticipated by earlier international projections. The key question is how low fertility can fall in modern societies where the key determinant may lie in social norms about ideal family size.

"People will always have children" is a quote attributed to both Winston Churchill and Konrad Adenauer (Abrahamson et al. 2005). The latter supposedly said it in reaction to an expert pointing out that the German pay-as-you-go pension system was rather vulnerable to the possibility of declining birth rates. This was in the early 1960s, when the Baby Boom was at its height and the TFR was well above the replacement level of 2.1. Soon thereafter, fertility rates in Germany entered a steep and lasting decline – currently hovering around 1.4, or two thirds of replacement level – putting the pension system under severe stress. Was Adenauer wrong?

While most existing world population projections agree that we are likely to see the end of world population growth (with a peak population of between eight and ten billion) during the second half of this century due to the on-going process of demographic transition from high birth and death rates to low ones, little has been said about the longer term future. The United Nations Population Division published projections for all countries until 2300 based on alternative fertility assumptions (United Nations 2004). However, the range of possible future fertility levels was extremely narrow, with the lowest level considered assuming a long term TFR of 1.85 and the highest scenario assuming 2.35. For the medium scenario exact replacement fertility is assumed which, by definition, results in long term constancy of population size in every country. Given that the long term 'floor' figure of 1.85 is significantly higher than the fertility Europe has experienced over the past 30 years and the recent ultra-low fertility experiences of East Asia, we sought to widen the scope of the very long-term projections by presenting an alternative set of convergence futures which range from the extremes of a longer term stalled fertility decline in Sub-Saharan Africa to

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the scenario of the whole world moving toward some of the lowest national TFRs currently found in the world.

2. Could global fertility levels fall to well below population replacement level?

Fertility levels well below replacement rate have been in evidence in many world regions for a number of decades. In Europe, traditionally thought of as being a vanguard in the transition to sub-replacement fertility, a large number of countries experienced 'lowest-low' fertility in the 1990s and early 2000s – defined as a period TFR of below 1.3 (Kohler et al. 2002). While most countries affected have seen their TFRs rise above this figure – not least through the 'tempo' effect of postponed childbearing on period measurement – the experience of low fertility made a profound impact upon both the policy and academic demographic discourse (Sobotka 2004; Frejka et al. 2008; Frejka & Sobotka 2008; Goldstein et al. 2009). Indeed, it is out of this new paradigm that a fundamental rethinking of some of the core precepts of the classical Demographic Transition model have developed, including the questioning of the two-child family model (Frejka 2008a). In 2002, therefore, when the UN broke from previous assumptions of convergence at around replacement and switched to 1.85 (United Nations 2003) – almost certainly in recognition of the new demographic regime in Europe – this was greeted as 'breaking the demographic sound barrier' (Wattenberg 2005) in terms of the global implications of below-replacement fertility.

However, how can we interrogate possible future trajectories of fertility? There is little doubt that from an evolutionary perspective our sex drive has been the main mechanism assuring the reproduction of the human species and that modern contraception has radically changed this pattern (e.g. Frejka 2008b). In this context, individual desires, ideals, and social norms are paramount for the decision to have a child. Indeed, fertility ideals and intentions have been described as powerful predictors of future fertility behaviour (Morgan & Rackin 2010).

One of the strongest social norms regarding childbearing in Europe is that of the normative power of the two-child ideal. In the Eurobarometer survey of EU countries, the percentage of people reporting two children as an ideal family size over the decade 2001-2011 rose from 52% to 57% for the general, or societal, ideal and from 49% to 52% for the personal ideal. By contrast, percentage of respondents aged 15-39 who state an ideal family size of one is just 10%, with 4% stating a desire to remain childless (Testa 2012).

This evidence is especially important in terms of how long-term projections are explicitly, and implicitly, designed. While the latest round of the UN's global population projections to 2100 are based upon a probabilistic model of fertility change, the end point of the projection model fluctuates around an asymptotic mean at replacement rate (United Nations 2011b). The implicit assumption behind this, therefore, is that the 'end point' of fertility transition is at, or around, replacement rate. Empirically, this would appear to be based upon the experiences of Northern- and Western-Europe and North America, which have seen relatively stable cohort and tempo-adjusted fertility rates of around replacement for some years. Despite the fact that the recent economic crisis has stalled fertility increases in many parts of Europe, the strength of the two-child norm as reflected in the Eurobarometer data supports the idea of an end point of fertility transition at, or around, two children (Sobotka et al. 2011; Testa 2012).

But what of the ultra-low fertility rates in evidence in East Asia? Following extremely rapid fertility decline, TFRs in Hong Kong SAR, Japan, Singapore, South Korea, and Taiwan have reached a global nadir of below 1.3 (Straughan et al. 2009; Boling 2008). Furthermore, local statistical offices in the region are pessimistic about an upturn in the short- and medium- term (e.g. HKCSD 2012; Basten 2013).

Crucially, however, a growing body of evidence exists to suggest that fertility ideals and intentions have also fallen to levels significantly below replacement level. In Taiwan in 2003, the mean ideal number of children among Taiwanese women was reported to be 1.8 while in Hong Kong a 2011 survey of young people found the ideal number of children to be as low as 1.5 (Basten et al. 2012). These are levels which are not currently observed in contemporary Europe. Furthermore, under the conditions of the so-called 'Low Fertility Trap' hypothesis, the normalisation of small family sizes as reflected through lower fertility ideals and intentions could mean that fertility rates become harder to raise in the future through family policy or other means (Lutz et al. 2006).

There is a massive natural experiment unfolding in the cities of China which demonstrates the existence of sizable human populations who voluntarily elect not to conform to a two-child norm. After two decades of a strict one-child policy, many young couples are now allowed, but frequently choose not, to have more than one child.

According to the 2010 Chinese Census, the resident population of Shanghai Municipality is 23.02 million (NBS 2011) – roughly the same as Australia or Sweden, Finland, Norway, Estonia, and Latvia combined. The TFR of the city's registered population – which accounts for 72.6% of the total population – has steadily declined from 1.23 in 1979 to below 1.0 by 1994 and reaching a nadir of 0.64 in 2003 with a recent slight upturn to 0.88 by 2008 (SMPFPC 2009a; SMPFPC 2009c). By 2000, other large Chinese urban centers saw a similar decline in fertility rates – such as Beijing (0.69) (Hou & Ma 2008) and Tianjin (0.91) (Gu 2009).

These ultra-low fertility rates go together with low mean childbearing intentions among Shanghai's registered population, which, according to surveys, have fallen from 2.04 in 1983 to just 1.07 in 2008 (SMPFPC 2009b; SMPFPC 2008), despite the fact that most couples would be free to have two children under the official policy as they are both only children. Such ultra-low fertility intentions can also be seen in other parts of China such as Beijing (1.23) (Hou & Ma 2008; Hou et al. 2008), Nanjing (1.21) (Wen et al. 2005) and elsewhere (e.g. Basten et al. 2012; Zheng et al. 2009; Wen & Zong 2006).

As with a wide variety of topics found in social surveys, respondents may frame their answers based upon not just personal views but within the nexus of social norms and what might be termed 'politically correct' attitudes. While surveys from a wide variety of settings and contexts have found a general correlation between fertility intentions and outcomes (e.g. Morgan & Rackin 2010), it is possible to argue that the 'politically correct' motivation of respondents in China may be particularly strong – especially given that the SMPFPC Survey was carried out by a Governmental organization. Hermalin and Liu (1990) compared face-to-face and anonymous methods of data collection of fertility preferences in the mid-1980s and found that the anonymous returns were generally higher, by up to 0.5 children. As such, even with this degree of uncertainty and building in such inflation, the levels reported for Shanghai are still well below replacement level.

Importantly, however, we can also identify the mean desired family size among the migrant population of Shanghai. This 'floating population' of workers hail from predominantly rural areas which are generally characterised by weaker family planning restrictions (such as the so-called 1.5-child policy where couples are allowed a second child if their first is a girl) and higher desired and realised fertility. However, even among this ‘floating’ population, the mean desired family size is just 1.30 among men and 1.36 among women (SMPFPC 2008).

While the Chinese family planning restrictions may be considered a unique episode in human history, it teaches us an important lesson that is relevant for the future of human reproduction: personal family size ideals can be greatly influenced by changing norms and social interaction and there can be situations for large populations in which the ideal – now voluntarily chosen and freely expressed – is heavily centred around just one (surviving) child.

Indeed, looking beyond East Asia we can see further fragmented pieces of evidence of ideal family sizes dropping below the European two-child norm. In India, for example, the 2005-06 *National Family Health Survey* found that 17.0% of women stated a preference for just one child. Among urban women this rose to 24.5%, while fully 30% of the richest and most educated women stated a preference for just one child (Basten & Kumara 2011).

In the *World Fertility Survey* and *Demographic and Health Surveys*, we can see that rapid declines in TFR have been accompanied by often dramatic falls in the ideal number of children desired. So much so that sub-replacement fertility ideals are already in evidence among younger cohorts in Vietnam, Bolivia, Peru, Colombia, El Salvador, Nepal (ICF International 2012), and Thailand (UNFPA 2011).

In conclusion, therefore, we suggest that the current paradigm of thinking around a two-child norm as the natural end point to fertility transition could, indeed, be challenged. This is especially so for countries whose recent economic, social, and educational development appears to more closely mirror the East Asian experience – not least in speed of change – rather than the European experience. To put it another way, many East Asian economies have reached extremely high levels of industrial capacity with some of the highest educational attainment rates in the world – all of which have been achieved with remarkable speed. As countries in Southeast Asia and South America industrialise and post high levels of economic growth and rapid fertility decline, could their fertility transition end point not be closer to South Korea than to Sweden?

Of course, these questions are entirely hypothetical – but we suggest that there is enough evidence to at least justify the exercise of examining possible very-long range global population futures beyond the rather narrow ranges of the UN’s projections, i.e. ‘below 1.85’. In doing so, we can understand the long-term global consequences of different trajectories of fertility which could provide a counterpoint to much of the current discourse concerning the population ‘explosion’.

3. Method

The calculations have all been carried out at the level of 13 world regions which follow the classification as used in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (Nakicenovic et al. 2000). The scenarios have been calculated on the basis of regular cohort-component projections by age (single years of age) and sex in single-year time steps up to 2300. While some agencies have produced probabilistic projections to 2100, we suggest that simply too little is known about living conditions and future technologies that would justify any probabilistic assessment beyond the end of the current century. As such, in order to maintain consistency in our methods we have utilised a deterministic cohort-component method for the purposes of this sensitivity analysis.

Until 2010 we used estimated vital rates from the latest revision of the UN's *World Population Prospects* which guaranteed our projections for 2010 were similar to the UN estimates for 2010 (United Nations 2011a).

Life expectancies for men and women are assumed separately, starting from the empirically given levels and are assumed to increase each by two years per decade until they reach the indicated level of maximum life expectancy – 90, 100, and 120 in the three scenarios. Because of different starting conditions, this maximum is reached at different points in time in different populations. After the maximum has been reached mortality is assumed to stay constant.

For fertility the indicated target level is assumed to be reached between 2030 and 2050 with linear interpolation between the current level and the target level. Here we distinguish between currently high and low fertility countries. For the low fertility regions (all parts of Europe, North America, Pacific OECD, and the China region) we assumed that the target level will be reached by 2030. For all other world regions we assumed that the indicated target level will be reached in 2050. For Africa, which currently has the highest level of fertility, two additional special scenarios have been calculated, one in which the target is only reached in 2070 and one in which fertility is assumed to remain stalled at a TFR of 5.0. For the last scenario the results are only presented to 2200 because they would quickly reach impossibly high levels.

For migration we made similar assumptions to the projections employed by the UN and those of the International Institute for Applied Systems Analysis (IIASA) which for convenience assume a slow phasing out of international migration. This is clearly unrealistic, particularly in view of the possible consequences of climate change, but has little effect on global population size, which is the main point of interest here. As such, we do not present the regional projections, rather a global aggregation.

Tables in the supplementary information list the results for selected years in terms of total population size and the proportion of the population above the age of 80. The labels for each column first give the target TFR and then after a hyphen the maximum life expectancy at birth which is assumed for the listed scenario.

4. Results

Figure 1 illustrates the longer term sensitivity of population size to even very small differences in fertility levels according to three different scenarios of life expectancy. In the 'central' mortality scenario of an asymptotic mean life expectancy of 100 years, by 2100 the difference between TFRs of 2.0 and 1.75 already amounts to almost 2 billion, increasing to over 5 billion by 2200 and 7 billion by 2300. A TFR of 2.25, on the other hand, would lead to continued massive growth reaching around 20 billion in 2200 and 30 billion in 2300. A TFR of 2.5 would result in a global population of 77 billion by 2300.

If, however, global fertility in the long run converged to a level of 1.5 – which is slightly below the 2009 average level in the European Union of 1.59 (Eurostat 2012) – then, after peaking around the middle of the century, the world population would return to the current level of seven billion people by 2100. By the end of the 22nd century it would then fall below three billion even though under this scenario, life expectancies would continue to increase until they reach 100 years in all parts of the world. Still lower fertility assumptions, based upon the kind of figures currently seen in East Asia, would result in more rapid declines and by 2200 in total world population sizes around one billion or below. The exact numbers for

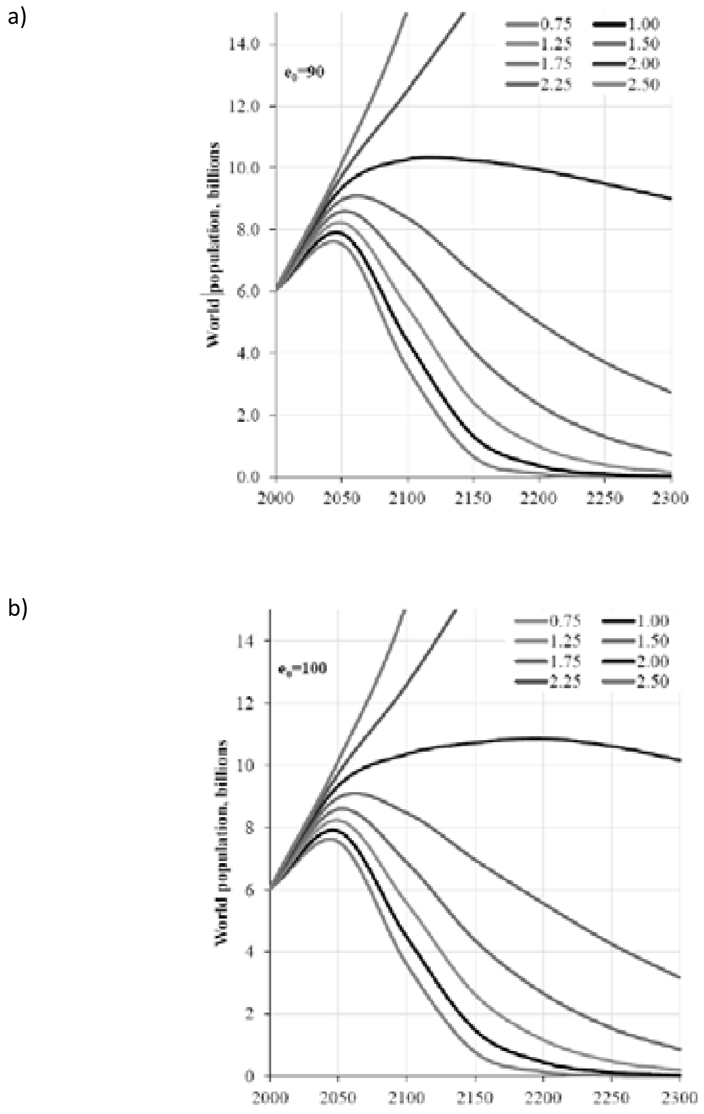

Figure 1. Global population size from 2000 to 2300 resulting from alternative global fertility levels as indicated (TFR to be reached by 2030-2050 and then kept constant) combined with a maximum life expectancy of (a) 90, (b) 100 and (c) 120 years

c)

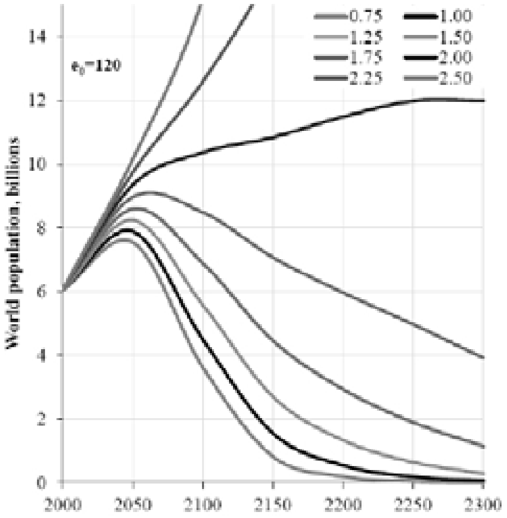

Figure 1. continued

Note: For sub-Saharan Africa, special stalled fertility decline scenarios were defined. For mortality, further improvements in life expectancy at two years per decade were assumed up until a certain maximum level. Maximum life expectancy was assumed to be 100 years (for listing of full set of results from alternative scenarios see supporting online text).

all scenarios, as well as the implications in terms of the age structures of the population, are listed in the appendix.

A final observation can be made concerning the relatively marginal contribution of changes in life expectancy to the overall quantum compared to the impact of alternate future patterns of fertility. Though this is demographically obvious, the relative insensitivity of the global sums to different patterns of mortality change is still worth highlighting.

5. Conclusions

We suggest the dominant two-child norm may not necessarily be the end point of transition as sizeable human populations exist where the *voluntarily chosen* ideal family size is heavily concentrated on just one child per woman with TFRs as low as 0.6-0.8. We have demonstrated the significant long term implications of possible sustained low fertility levels by producing the first global population projections into the twenty-second and twenty-third centuries based on a broader range of alternative fertility levels.

A global move to the fertility levels seen in a number of Chinese urban centres (around 0.75) over the coming 40 years would result in a peaking of global population before 2050 and a decline to only 3.6 billion in 2100 and 150 million people by 2200. But even the more realistic range of long term fertility levels of 1.5-1.75 (higher than it has been in much of Europe for the past decades) would lead to declines in global population size of 2.6-5.6 billion by 2200 and even 0.9-3.2 billion by 2300. Therefore, even under conditions of further substantial increases in life expectancy, world population size would decline significantly if the world, in the longer run, followed the examples of Europe and East Asia.

The one continent where such a future looks most doubtful is Africa. In several sub-Saharan African countries the fertility decline is not proceeding well or may even have stalled (Ezeh et al. 2009; Bongaarts 2008). For this reason we calculated a number of additional scenarios for Sub-Saharan Africa with a population of currently around 700 million (see supporting materials, Appendix 2). If the target fertility levels are only reached by 2070 instead of 2050, a TFR of 2.0 would result in 2.9 billion instead of 2.0 billion in 2100. If fertility remained completely stalled around the current fertility level of 5.0 already in 2100, the population size of Sub-Saharan Africa would reach a stunning 12 billion and a sheer impossible 355 billion by 2200. If fertility continued to stay at such high levels it is not implausible to assume that population growth would be checked through increasing mortality. It is worth noting that future decline in Africa is far from being a certainty and that, in analogy to the above described 'Low Fertility Trap', there may be a high fertility trap mechanism in which rapid population growth inhibits the development that would bring down fertility (Dasgupta 1993; King 1990). Past experience has shown that the best way to break this vicious circle is the combination of female education with provision of family planning services (see, for example, Bongaarts & Sinding 2011; Lutz 2009; Jejeebhoy 1995).

Is a future with long term global fertility below two and, hence, long term population decline something to be concerned about? Ecologists have long demanded a smaller world population size with a lighter ecological footprint and assumed, in the spirit of Malthus, that this will come naturally as a consequence of higher mortality caused by overpopulation and the resulting disasters. Our calculations clearly demonstrate that this desired decline can be reached even under conditions of further increasing life expectancy.

What about the problems of rapid population aging resulting from low fertility? In the long run, the age structure will stabilize under constant fertility and mortality rates even when the population is shrinking. The tables in the online supporting materials clearly illustrate this for the proportion above the age of 80 which eventually stabilizes. But over the coming decades the still accelerating speed of ageing (Lutz et al. 2008) seems to be the main problem because it requires a higher speed of adjusting social support and pension systems. Here the good news, however, lies in the on-going trend of improving health among the elderly, which can be assumed to continue into the future. Furthermore, if education and human capital is factored in, it has recently been suggested that a fertility level of 1.6-1.8 could be optimal even from an age-dependency perspective, if the smaller cohorts are better educated and therefore more productive (Lutz et al. 2012). Hence in the future the focus on population size and age structure should be complemented by one on education and health (Cohen 2008; Lutz et al. 1998). Finally, it is likely that these fewer and more empowered people would be better able to cope with, and adapt to, climate change.

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3 Measuring Aging

Introduction

Warren C. Sanderson and Stefanie Andruchowitz

We have worked with Sergei for many years in a variety of roles. The idea motivating our work is simple. It is to view people on the basis of what they can do rather than on the number of birthdays they have had. We have both worked with Sergei on papers, policy briefs, grant proposals, datasheets, press releases, and everything else that goes into the work of a scholar challenging entrenched ideas.

Sergei's work goes beyond writing papers. He has publicized his research with creative datasheets that now hang in offices all over the world and he is high demand as a teacher. Less well-known is that Sergei is the personification of his own ideas. After writing a paper on using handgrip strength as an indicator of the speed of aging across population subgroups (Sanderson & Scherbov 2014b, this volume), he was given a dynamometer, the instrument used to measure handgrip strength. Every now and then, when the topic arises, Sergei takes out the dynamometer and lets people test their handgrip strength. We can report that Sergei has a handgrip strength greater than most people half his age.

People understand that there is a difference between one's chronological age and an age that reflects what they can do. They regularly say "40 is the new 30." They intuitively understand what these phrases mean, but the scientific basis for them was unclear before Sergei began his work on aging.

Sergei did not begin his work on aging by thinking about who is old and who is not. He began it in 2005 with an article in *Nature* entitled *Average Remaining Lifetimes Can Increase as Human Populations Age* (Sanderson & Scherbov 2005, this volume). This raised the question as to how people should think about age in an environment where life expectancies were increasing. Picture a rubber band with a mark somewhere in the middle. The distance between the left end of the rubber band is the average number of years that people have already lived and the distance from the mark to the right end of the rubber band is their average remaining lifetimes. Stretching the rubber band is like increasing life expectancy. The distance from the left end of the rubber band to the mark is now greater, so the average number of years that people have lived is greater and the population has aged. But then look at the distance from the mark to the right end of the rubber band. This has grown longer too; thus, average remaining lifetimes have also increased. As life expectancies increase, both the number of years lived and the average number of years left to live can increase. Forty could be the new 30 in the sense that after their life expectancy increases, 40-year-olds could have the same longevity as 30-year-olds used to have.

Thus, Sergei's research on aging began with a reconceptualization of the concept of age itself. This reconceptualization has led to the series of articles that follow this introduction. In Sanderson and Scherbov (2013, this volume), the concept of age was generalized further to include a wide variety of possible dimensions, including alternative ages based on hand-grip strength, disability, and self-reported health. In his articles, these alternative ages are called alpha-ages.

Research can result in unanticipated outcomes. This has been especially true with respect to the use of alternative ages. Using these, Sergei found a counterintuitive result. Faster increases in life expectancy at older ages lead to slower population aging (Sanderson & Scherbov 2015, this volume). It also turned out that the alternative ages were exactly what was needed to define intergenerationally equitable public pension ages (Sanderson & Scherbov 2014a, this volume).

Looking across countries, the use of measures based on alternative ages indicates that population aging will come to an end during this century in a variety of countries, including China, Germany, and the USA (Sanderson et al. 2017). Alternative age measures also help to redefine the onset of old-age and related public policies. Public policies based on a functional definition of the onset of old age are less likely to lead to fiscal or other types of problems as the demographic environment changes.

In addition to publishing journal articles, Sergei has been communicating with a broader audience through alternative channels. Examples of this include *Rethinking Age and Aging*, a Population Bulletin published by the Population Reference Bureau (Sanderson & Scherbov 2008) and the IIASA Policy Brief, *Analyzing Population Aging from a New Perspective* (Sanderson, Scherbov & Andruchowitz 2016). Since 2006 Sergei has significantly contributed to the publication of demographic data sheets that present the latest demographic data for the world, world regions, and a large number of countries in a comprehensive way. The two most recent issues, the European Data Sheet and the Russian Data Sheet paid special attention to the importance of alternative indicators of population aging (VID & IIASA 2016; RANEPA et al. 2016). The importance of Sergei's work for research, policy making and societies as a whole, was recognized by the European Research Council when Sergei received an Advanced Grant of €2.25 million in 2012 to develop his ideas further. He is now leading an international team of scientists who are applying the alternative measures of aging in a variety of innovative ways (Sanderson, Scherbov, Weber, et al. 2016; Scherbov & Ediev 2016; Gietel-Basten et al. 2015; Sanderson & Scherbov 2016; Scherbov et al. 2016; Bordone et al. 2015).

Sergei puts immense effort into training and education. He understands that young scientists from around the world will be leading the discourse on aging and advising policy makers in the future. He has taught over 60 intensive courses in advanced demographic analysis, population projections, and computer applications in different settings around the world since the beginning of his career. Universities in Asia, Europe and North America, as well as the United Nations Population Fund (UNFPA) have invited him repeatedly to hold training courses for junior scientists, academics, statistical experts, and government agencies. For 34 years he has been refining his teaching approach and has stayed continuously up-to-date. This has earned him a high reputation among peers and professionals and explains the large number of applications for each of his courses.

Sergei's students come from a wide variety of backgrounds, but he always manages to teach them practical tools and new ideas that can be implemented in their own research and work lives. Sergei works intensively with each student finding every odd number and every bug in their homework assignments. His excitement before and during each course is contagious and neither his students nor his colleagues are immune to it. Whether you are an established scholar or a young student, there is no better way of learning about demography in general and population aging in particular than by interacting with Sergei.

We have had the pleasure to be part of his team and to work with him in developing his ideas further. We are happy to report that the research, policy papers, datasheets, and teaching are all continuing at full speed regardless of Sergei's upcoming 65th birthday. We expect that his spirit and enthusiasm will continue to propel his work onwards and upwards in the coming decades. We certainly should not consider someone who is 60 or 65 to be old. People now are much healthier and much "younger" than their counterparts in previous generations. Sergei is the best example for his own theories; his biological age might be 65, but his real age is 55. Happy birthday, Sergei!

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Average Remaining Lifetimes Can Increase as Human Populations Age[1]

Warren C. Sanderson and Sergei Scherbov

Increases in median ages, the most commonly used measure of population ageing (Gavrilov & Heuveline 2003; United Nations 2005), are rapid in today's wealthier countries (Sanderson et al. 2004; United Nations 2005), and population ageing is widely considered to be a significant challenge to the well-being of citizens there (Peterson 1999). Conventional measures of age count years since birth; however, as lives lengthen, we need to think of age also in terms of years left until death or in proportion to the expanding lifespan. Here we propose a new measure of ageing: the median age of the population standardized for expected remaining years of life. We show, using historical data and forecasts for Germany, Japan and the United States, that although these populations will be growing older, as measured by their median ages, they will probably experience periods in which they grow younger, as measured by their standardized median ages. Furthermore, we provide forecasts for these countries of the old-age dependency ratio rescaled for increases in life expectancy at birth (Lee & Goldstein 2003). These ratios are forecasted to change much less than their unscaled counterparts, and also exhibit periods when the population is effectively growing younger.

Population ageing differs from the ageing of an individual. People who survive grow older with each year they live. Populations, on the other hand, can grow younger. Because a wide variety of matters such as the cost of medical care (Miller 2001; Seshamani & Gray 2004; Stearns & Norton 2004), retirement (Hurd et al. 2004), bequests (Gan et al. 2004), consumption (Lee & Tuljapurkar 1997) and the accumulation of human (Creighton & Hudson 2002) and tangible (Bloom et al. 2003; Higgins 1998) capital depend not only on age but also on time left to live, our understanding of population ageing must also reflect both of these factors. Because conventionally measured old-age dependency ratios (the ratio of the number of people at the retirement age and above divided by the number of people in the working ages) have caused worry about the sustainability of pensions (Disney 2000), it is important to recognize that these ratios, rescaled for life expectancy increases, are forecasted to change comparatively little over the century, suggesting caution in our assessment of long-term pension problems.

Figure 1a–c and Supplementary Table 1 provide information about the unstandardized median age of the population, the standardized median age of the population, using the country's (Germany, Japan, United States) life table in 2000 for standardization, and the remaining life expectancy at the unstandardized median age. All figures pertain to both sexes combined and are calculated using period life tables. There are two types of data: the values through to 2000 are observed, whereas those for future years are based on 1,000 stochastic forecasts.

The median age is the age that divides a population into two numerically equal groups, with half of the people being younger than this age and half older. Life expectancy at the median age is the expected number of years to be lived by a person at the median age. It is also the median remaining life expectancy in the population, with half of the people being at ages with lower remaining life expectancies and half at ages with higher ones. Life

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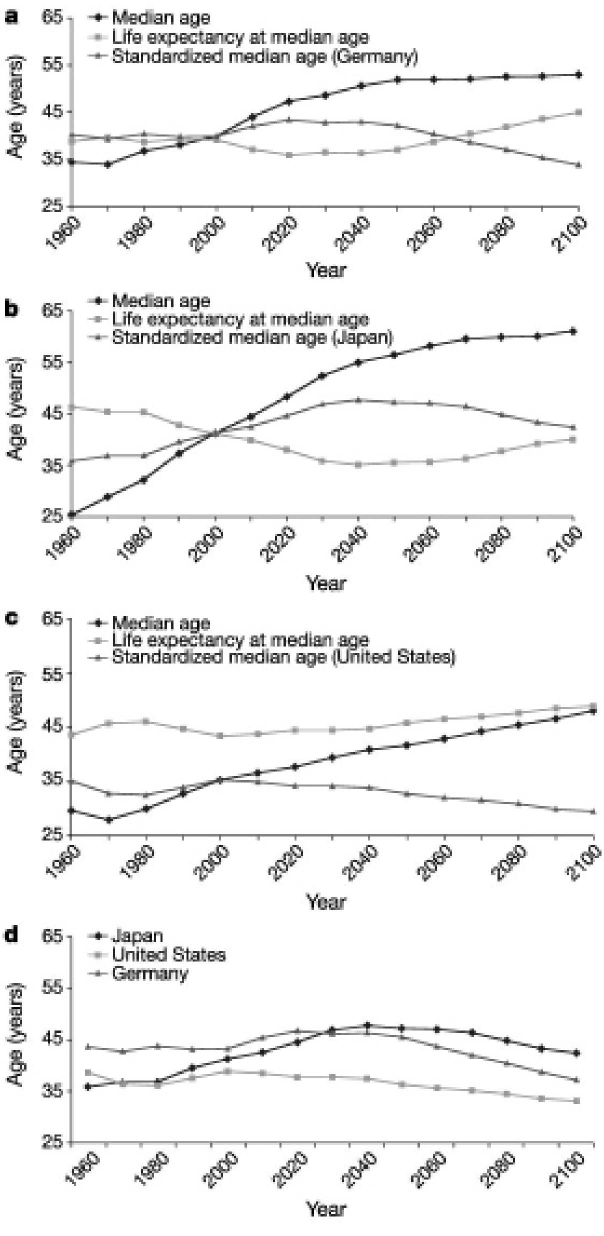

Figure 1. Unstandardized and standardized median ages, and life expectancies at unstandardized median ages. a, Germany; b, Japan; c, United States. a-c, Standardized median ages based on country-specific life tables for 2000. d, Standardized median ages based on Japanese life table for 2000. The values through to 2000 are observed; later values are medians based on 1,000 simulations (for 95% prediction intervals see Supplementary Table 1). All values are based on period life tables.

expectancy at the median age is especially easy to use as an indicator of ageing because it is comparable both across countries and over time.

Medical care expenditures provide an example where calculating the median remaining life expectancy in a population is useful. Health care costs rise rapidly in the last years of a person's life. The change in the median remaining life expectancy between years is equal to the change in the median time to the onset of that phase of rapidly rising costs.

For many of the decades both the median age and the life expectancy at the median age increase. For the three countries, mortality rates at young ages are now quite low and most of the rise in life expectancies at birth derives from life expectancy increases at the older ages. If the median age of the population remained fixed, remaining life expectancy at the median age would surely increase. However, the essence of population ageing is the increase in median ages. If median ages increase slowly, remaining life expectancies at the median age will increase. On the other hand, median ages can increase so rapidly relative to improvements in mortality rates that remaining life expectancies fall.

An example of a rapid increase in median age outrunning survival rate increases can be seen for Japan between 2000 and 2040 (Fig. 1b). Here, the median age is expected to rise from 41.3 yr to 55.0 yr while the life expectancy at the median age falls from 41.1 yr to 35.0 yr. In the remaining 60 yr of the century, Japan provides an example of where slower increases in the median age are associated with gains in life expectancy at the median age. One broad conclusion from Fig. 1a–c for all three countries is that even in the presence of significant ageing, as measured by increases in the median age, life expectancies at the median age are likely to change only moderately.

Median ages in a country change because of prior changes in fertility, mortality and migration rates. In Japan, the median age is rising rapidly because of a combination of relatively low fertility, high life expectancy and little migration. The United States stands at the opposite end of the spectrum. Its slow increase in median age is a result of relatively high fertility, somewhat lower life expectancy and substantial migration. Germany has demographic rates between those of Japan and the United States.

One disadvantage of using life expectancy at the median age as a measure of ageing is that it is not directly comparable to the median age itself. For comparability it is useful to have another median age, one based on the expected number of years a person has left to live. This is the standardized median age.

The life expectancy standardized population is the hypothetical population that arises when the age of each individual in a specific year is changed to the age of the person in 2000 who had the same remaining life expectancy. For example, if a 40-yr-old person in 2050 had a remaining life expectancy of 50 yr, and a 30 yr old had the same remaining life expectancy (50 yr) in 2000, then the 40-yr-old person would be assigned an age of 30 in the life expectancy standardized population. By definition, when the standardization is done using the country's own life table, the median age and the standardized median age of the population are the same in 2000.

Median ages in the three countries generally increase over time; however, standardized median ages show a different pattern of change. In the United States, the standardized median values of the forecasted distributions fall continuously from 2000 onwards, whereas in Germany and Japan, they first increase at the beginning of the century and then decrease. A decreasing standardized median age is far from a certainty in the United States. The 95% prediction intervals for all years from 2010 to 2100 include the value of the standardized median age in 2000 (see Supplementary Table 1). We also show in Supplementary Table 1 that an increase in the standardized median age in first decades of the century seems almost certain in Germany and Japan.

Although we are confident that ageing will occur throughout the century in all three countries as measured by the unstandardized median age, we are also sure that much less ageing or even some increase in youthfulness will be observed using the concept of the standardized median age. When considered from different perspectives, populations in some periods will be growing simultaneously younger and older.

In Fig. 1d, we plot the median ages for the three countries standardized using the 2000 Japanese life table. When the standardization is done with a single country's life table, standardized median ages are comparable across countries. We use Japan as the standard because it had the highest life expectancy among all the countries of the world in 2000. At the beginning of this century, the differences in standardized median ages across the countries were relatively small. The difference between the highest standardized median age (43.2 in Germany) and the lowest (38.8 in the USA) was 4.4 yr. At mid- century the gap in the median forecasts widens significantly to 10.9 yr, with Japan having the highest value and the USA continuing to have the lowest. In 2050, Japan's population will be considerably older than that of the USA both in terms of the unstandardized and standardized median ages.

Figure 2a–c provides a second perspective on ageing using the concept of proportional life cycle rescaling5. Proportional life cycle rescaling is a heuristic not a predictive concept. It provides one simple way of thinking about a complex future in which the lengths of life cycle phases will be influenced by social policies and demo- graphic constraints not modelled here. We use proportional life cycle rescaling by adjusting the conventional start of the working age phase (assumed to be age 20 in the year 2000) and the conventional end of that phase (assumed to be age 65 in 2000) proportionally to changes in life expectancy from 2000 onward. Figure 2a–c contains conventional measures of the old-age dependency ratio and new versions of these measures calculated assuming proportional life cycle rescaling.

For all three countries the conventional old-age dependency ratio increases markedly over the century. In Germany, it rises from 0.261 in 2000 to a median forecasted value of 0.797 in 2100. In Japan, the increase is larger, going from 0.276 in 2000 to 1.118 in 2100. In the United States, the increase is smaller than in Germany, but the conventional measure still triples over the century.

The rescaled values show a different pattern. The rescaled old-age dependency ratios rise initially in all three countries and then fall. The rise is quite likely, with the 95% prediction interval in 2040 lying entirely above the ratio in 2000 for all three countries (see Supplementary Table 2). After the middle of the century, changes in the ratio are unclear because the magnitudes of the declines are small relative to the uncertainty involved. For all three countries, the rescaled old-age dependency ratios show considerably less change than the conventional ones.

The new measures presented here are not meant to supplant existing measures, but to supplement them. A perspective that incorporates the new measures presented here is crucial if we are to understand and react appropriately to the challenges of population ageing.

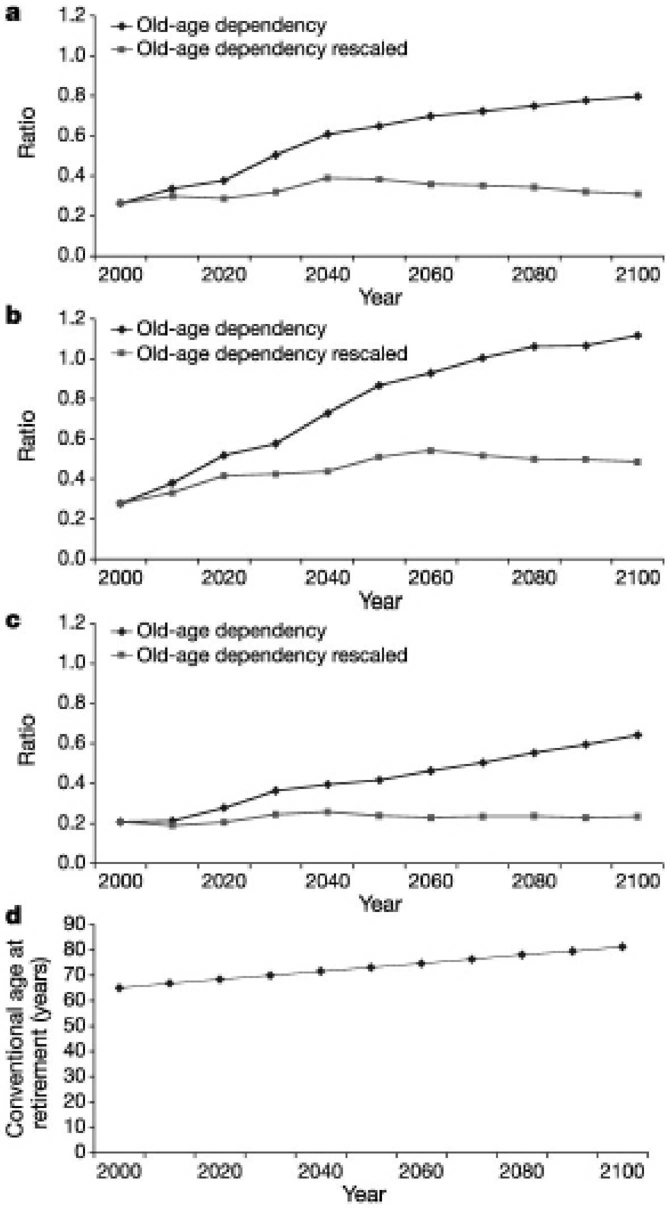

Figure 2. Conventional and rescaled old-age dependency ratios. a, Germany; b, Japan; c, United States. The old-age dependency ratio is the ratio of the number of people at the retirement age and above divided by the number of people in the working ages. Rescaling increases ages at the beginning and end of working interval proportionally to changes in life expectancy at birth. d, Proportionally adjusted retirement ages in Japan. The values for 2000 are observed; later values are medians based on 1,000 simulations (for 95% prediction intervals see Supplementary Table 2). All figures are based on period life tables.

Methods

The probabilistic forecasts make use of our previously published method- ology (Lutz et al. 2001; Lutz et al. 2004) specialized to the individual countries. In our previous work, we used a mean total fertility rate (TFR) of 2.0 for North America in 2082. Here we use a mean TFR of 1.85 for the United States in that year. This is slightly lower than the one assumed by the United Nations. A lower TFR increases the standardized median age of the population because it results in a smaller number of young people. In our earlier work, we assumed a mean TFR of 1.6 in the region comprised of Japan, Australia and New Zealand in 2082, which is dominated by the population of Japan. We used the same TFR for Japan at that date. We also assumed a mean TFR of 1.7 for Western Europe in 2082. Here we assume a mean TFR of 1.6 for Germany in 2082, because its fertility has been below the average for Western Europe for the last three decades. We assume that distributions around the means are normal with a 90% chance of observing an outcome within half a child of the mean.

Our mortality assumptions are also very similar to those made for the corresponding regions in our earlier work. Life expectancy increases were assumed to have a mean value of 2 yr per decade with a 90% chance of an outcome within 1 yr of the mean. This is consistent with observations over the past four decades (Sanderson & Scherbov 2004) and other recently published work (Oeppen & Vaupel 2002). Our migration assumptions were made using the same procedure as in our earlier work, except that they were based on observations for the specific countries.

Figure 2d shows the evolution of the rescaled conventional age at retirement in Japan. The paths for Germany and the USA are almost identical. By construction, this age is 65 in 2000. Using our life expectancy forecasts and the proportionality hypothesis, the median forecasted conventional age rises to 73 by 2050 and continues to climb for the remainder of the century. These rescaled conventional ages are used in the production of Fig. 2.

Forecasted data in Figs 1 and 2 are the median values of the forecast distributions based on 1,000 simulations. The median values and their 95% prediction intervals are presented in Supplementary Tables 1 and 2. In each year, we compute the median age of the population. These median ages depend on the age distribution of the population at the beginning of the forecast period and on the whole time paths of fertility, mortality and migration rates from the beginning of the forecast period to the year in question.

We calculate the distribution of remaining life expectancy at the median age in year t, for example, using the stochastic life table associated with that year. Thus, life expectancies at the median age in year t have uncertainty due to variability in median ages in year t and due to the randomness in the life tables for that particular year. The life table used in period t is closely associated with the time path of life tables before year t and therefore with the age structure and the median age of the population in that year. Standardized median ages are also subject to both sorts of uncertainty.

The uncertainty in the distributions of remaining life expectancy and the distributions of standardized ages are influenced by the correlations between the median age at time t and life expectancy at time t. The autocorrelation of life expectancies implies that a high life expectancy at time t is associated, on average, with a high median age in that year. High life expectancies and high median ages have opposing effects on the remaining life expectancy at the median age, reducing the uncertainty relative to what it would have been in the absence of those correlations.

The differences in sources of uncertainty can be seen in Supplementary Table 1 by comparing the size of the 95% prediction intervals for unstandardized and standardized median ages. For Germany in 2020, for example, the difference between the upper and lower bounds of the 95% prediction interval for the unstandardized median age is 1.8 yr. The comparable difference for the standardized median age (using either the German or Japanese standards) is 3.8 yr.

The observed median ages and the life expectancies at the median age move less regularly than the forecasted medians. The observed figures take baby booms and busts into account differently. The observed figures are from a single random path of realizations for each country. The forecasted medians essentially average across possible future paths and are therefore much smoother.

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Supplementary Information for “Average Remaining Lifetimes Can Increase as Human Populations Age”[1]

Warren C. Sanderson and Sergei Scherbov

Supplementary Table 1A. Unstandardized median age, life expectancy at the median age (median expected remaining years of life), standardized median age (German standard), and standardized median age (Japanese standard), Germany, 1960 to 2100.

Year	Median Age Unstandardized	Life Expectancy at Median Age	Median Age Standardized (Germany, 2000)	Median Age Standardized (Japan, 2000)
1960	34.5	38.9	40.3	43.6
1970	34.0	39.7	39.4	42.7
1980	36.8	38.7	40.4	43.7
1990	38.2	39.3	39.8	43.1
2000	39.9	39.2	39.9	43.2
2010	44.1 (43.9-44.2)	37.2 (36.3-38.0)	42.1 (41.1-43.0)	45.4 (44.5-46.3)
2020	47.4 (46.4-48.2)	35.9 (34.1-37.6)	43.4 (41.6-45.4)	46.7 (44.9-48.7)
2030	48.6 (46.9-50.4)	36.5 (33.7-39.2)	42.8 (39.9-45.8)	46.1 (43.2-49.1)
2040	50.6 (48.0-53.4)	36.3 (32.6-40.1)	43.0 (39.0-47.0)	46.3 (42.3-50.3)
2050	51.9 (47.9-56.6)	37.1 (32.3-41.9)	42.2 (37.0-47.4)	45.5 (40.3-50.7)
2060	51.9 (47.0-57.9)	38.8 (32.4-45.0)	40.3 (33.8-47.3)	43.7 (37.1-50.6)
2070	52.1 (46.6-58.9)	40.4 (33.2-48.0)	38.7 (30.7-46.4)	42.0 (34.0-49.7)
2080	52.6 (46.0-60.6)	41.9 (33.7-50.2)	37.1 (28.5-45.8)	40.4 (31.8-49.1)
2090	52.6 (45.4-62.1)	43.5 (34.4-53.5)	35.3 (25.1-45.0)	38.7 (28.4-48.3)
2100	53.0 (45.5-63.4)	45.0 (35.1-55.7)	33.8 (22.7-44.3)	37.1 (26.1-47.6)

Note: The figures through 2000 are observed. The figures from 2010 to 2100 are medians (and in parentheses 95 percent prediction intervals) based on 1,000 simulations. All figures are based on period life tables.

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[1] published online on the website of *Nature*

Supplementary Table 1B. Unstandardized median age, life expectancy at the median age (median expected remaining years of life), and standardized median age (Japanese standard), Japan, 1960 to 2100.

Year	Median Age Unstandardized	Life Expectancy at Median Age	Median Age Standardized (Japan, 2000)
1960	25.3	46.3	35.8
1970	28.8	45.3	36.8
1980	32.1	45.3	36.8
1990	37.4	42.8	39.5
2000	41.3	41.1	41.3
2010	44.4 (44.3-44.5)	39.9 (39.1-40.7)	42.5 (41.6-43.3)
2020	48.3 (47.8-48.8)	38.0 (36.2-39.6)	44.6 (42.8-46.4)
2030	52.4 (51.2-53.5)	35.8 (33.5-38.2)	46.8 (44.3-49.4)
2040	55.0 (52.6-57.3)	35.0 (32.0-38.3)	47.7 (44.2-51.0)
2050	56.4 (52.9-60.1)	35.5 (31.5-39.4)	47.2 (43.0-51.6)
2060	58.2 (53.6-62.5)	35.6 (30.5-41.2)	47.1 (41.1-52.7)
2070	59.5 (52.7-65.5)	36.3 (29.7-42.9)	46.3 (39.4-53.5)
2080	59.9 (51.7-67.9)	37.7 (30.4-45.8)	44.8 (36.3-52.8)
2090	60.1 (52.0-69.5)	39.2 (30.7-47.9)	43.3 (34.1-52.5)
2100	61.1 (51.5-71.2)	40.0 (31.1-50.5)	42.4 (31.4-52.1)

See Note to Supplementary Table 1A.

Supplementary Table 1C. Unstandardized median age, life expectancy at the median age (median expected remaining years of life), standardized median age (US standard), and standardized median age (Japanese standard), USA, 1960 to 2100.

Year	Median Age Unstandardized	Life Expectancy at Median Age	Median Age Standardized (USA, 2000)	Median Age Standardized (Japan, 2000)
1960	29.6	43.6	35.1	38.6
1970	27.9	45.7	32.8	36.4
1980	29.9	46.0	32.5	36.1
1990	32.7	44.7	33.9	37.5
2000	35.3	43.5	35.3	38.7
2010	36.6 (36.3-36.8)	43.8 (42.9-44.6)	34.9 (34.0-35.7)	38.4 (37.6-39.3)
2020	37.7 (36.9-38.5)	44.4 (42.6-46.3)	34.2 (32.2-36.2)	37.7 (35.8-39.7)
2030	39.4 (37.9-41.0)	44.5 (41.6-47.3)	34.1 (31.2-37.2)	37.7 (34.8-40.7)
2040	40.9 (38.3-43.8)	44.8 (41.1-48.9)	33.8 (29.4-37.7)	37.4 (33.1-41.2)
2050	41.7 (38.4-45.8)	45.8 (40.6-51.0)	32.7 (27.3-38.3)	36.3 (30.9-41.8)
2060	42.9 (38.6-47.7)	46.5 (40.0-53.2)	32.0 (25.0-38.9)	35.6 (28.7-42.4)
2070	44.2 (39.1-49.8)	47.0 (39.5-54.8)	31.5 (23.3-39.4)	35.1 (27.0-42.9)
2080	45.4 (39.6-52.4)	47.6 (39.3-56.4)	30.8 (21.6-39.7)	34.4 (25.4-43.2)
2090	46.6 (40.5-54.5)	48.5 (39.5-58.2)	29.9 (19.7-39.5)	33.5 (23.6-43.0)
2100	48.0 (41.3-56.6)	48.9 (39.0-60.0)	29.5 (17.8-40.0)	33.1 (21.7-43.5)

See Note to Supplementary Table 1A.

Supplementary Table 2A. Conventional and Rescaled Old Age Dependency Ratios, Germany, 2000- 2100.

Year	Old Age Dependency Ratio	Old Age Dependency Ratio (Rescaled)
2000	0.261	0.261
2010	0.335 (0.331-0.339)	0.297 (0.283-0.312)
2020	0.376 (0.357-0.395)	0.287 (0.259-0.320)
2030	0.504 (0.459-0.550)	0.318 (0.265-0.387)
2040	0.607 (0.524-0.699)	0.389 (0.304-0.484)
2050	0.648 (0.532-0.800)	0.382 (0.310-0.484)
2060	0.698 (0.548-0.909)	0.358 (0.266-0.488)
2070	0.722 (0.550-0.979)	0.351 (0.244-0.488)
2080	0.749 (0.543-1.057)	0.343 (0.236-0.490)
2090	0.777 (0.544-1.148)	0.320 (0.215-0.480)
2100	0.797 (0.553-1.209)	0.309 (0.185-0.479)

Note: The figures for 2000 are observed. The figures from 2010 to 2100 are medians (and 95 percent prediction intervals in parentheses) based on 1,000 simulations. All figures are based on period life tables.

Supplementary Table 2B. Conventional and Rescaled Old Age Dependency Ratios, Japan, 2000- 2100.

Year	Old Age Dependency Ratio	Old Age Dependency Ratio (Rescaled)
2000	0.276	0.276
2010	0.380 (0.377-0.383)	0.333 (0.314-0.352)
2020	0.518 (0.500-0.537)	0.417 (0.374-0.458)
2030	0.577 (0.535-0.619)	0.425 (0.384-0.475)
2040	0.730 (0.654-0.809)	0.438 (0.366-0.531)
2050	0.867 (0.747-1.010)	0.510 (0.397-0.638)
2060	0.929 (0.762-1.140)	0.543 (0.426-0.668)
2070	1.005 (0.773-1.326)	0.518 (0.395-0.657)
2080	1.062 (0.766-1.459)	0.499 (0.361-0.677)
2090	1.066 (0.741-1.557)	0.497 (0.350-0.695)
2100	1.118 (0.755-1.660)	0.487 (0.328-0.695)

Note: See Note to Supplementary Table 2A.

Supplementary Table 2C. Conventional and Rescaled Old Age Dependency Ratios, USA, 2000- 2100.

Year	Old Age Dependency Ratio	Old Age Dependency Ratio (Rescaled)
2000	0.209	0.209
2010	0.213 (0.211-0.215)	0.189 (0.177-0.200)
2020	0.276 (0.266-0.287)	0.206 (0.179-0.238)
2030	0.362 (0.335-0.391)	0.245 (0.198-0.297)
2040	0.394 (0.347-0.449)	0.257 (0.211-0.315)
2050	0.416 (0.352-0.501)	0.238 (0.187-0.311)
2060	0.462 (0.379-0.582)	0.230 (0.162-0.320)
2070	0.504 (0.400-0.651)	0.235 (0.155-0.333)
2080	0.553 (0.412-0.742)	0.237 (0.156-0.350)
2090	0.594 (0.432-0.855)	0.229 (0.148-0.356)
2100	0.641 (0.455-0.933)	0.234 (0.135-0.370)

Note: See Note to Supplementary Table 2A.

Remeasuring Aging[1]

Warren C. Sanderson and Sergei Scherbov

Population aging is an international concern, in part because of consequences of coming age-structure changes, e.g., growth in the number of elderly, decline in the number of youth, and accompanying economic and social costs (Cotis 2003; OECD 2005; Peterson 1999; United Nations 2009a). These expectations are based on conventional measures of aging that link expected phenotypes to fixed chronological ages. But as life expectancies increase and people remain healthy longer, measures based solely on fixed chronological ages can be misleading. Recently, we published aging forecasts for all countries based on new measures that account for changes in longevity (Lutz et al. 2008; Sanderson & Scherbov 2005; Sanderson & Scherbov 2007; Sanderson & Scherbov 2008b). Here, we add new forecasts based on disability status. Both types of forecasts exhibit a slower pace of aging compared with the conventional ones.

Limits to Chronological Age

One advantage of aging forecasts based on fixed chronological ages (United Nations 2001; United Nations 2007; United Nations 2009a) is that the United Nations (UN) computes them consistently for all countries of the world. These include the proportion of the population 65 and older, and the old-age dependency ratio (OADR), which considers people dependent upon others when they reach the age of 65 (often calculated as the number of people aged 65 or older, divided by the number of people of working age, 15 or 20 to 64). When using indicators that assume fixed chronological ages, it is implicitly assumed that there will be no progress in important factors such as remaining life expectancies and in disability rates. But many age-specific characteristics have not remained fixed and are not expected to remain constant in the future (United Nations 2009b). In 1950, for example, 65-year-old women in Canada, Sweden, and the United States could expect to live an average of around 15 more years. By 2000, that had risen to about 20 (University of California, Berkley, CA & Max Planck Institute for Demographic Research (Germany) n.d.), and the UN foresees further increases. Other forecasts also assume continuation of trends in life expectancy growth seen in the last decades (Lutz et al. 2008; Oeppen & Vaupel 2002), although the UN forecasts assume that the speed of life expectancy increases will slow.

Disability-free life expectancies, which describe how many years of life are spent in good health, have also been increasing, often as fast as unconditional life expectancies, because of decreases in age-specific disability rates (Bhattacharya et al. 2004). For example, in the United States, the proportion disabled in the age group 65 to 74 declined from 14.2% in 1982 to 8.9% in 2004-05 (Manton et al. 2006a). Thus, fixed chronological ages do not work well in evaluating the effect of age structure changes on health care costs, because most of those costs occur in the last few years of life, which happen at ever later ages as life expectancies increase (Christensen et al. 2009; Shultz & Shoven 2008).

Life-Expectancy Adjustments

Defining old age by using life expectancy instead of chronological age was first suggested in (Ryder 1975), and expanded upon in (Siegel 1993). The more general point that ages could be adjusted for life-expectancy change much as financial variables

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are adjusted for inflation appeared first in (Fuchs 1984). Forecasts of aging that take life expectancy into account are relatively easy to compute, but several issues contributed to their remaining underexplored. For example, concern about aging was less a priority until relatively recent years. And before publication of (Sanderson & Scherbov 2008a), life-expectancy adjustments were not available in a consistent format for all countries, and people were not trained in their use.

Alternative measures that account for life-expectancy changes show slower rates of aging than their conventional counterparts (Lutz et al. 2008; Sanderson & Scherbov 2005; Sanderson & Scherbov 2008a). For example, an alternative to the OADR is the prospective old age dependency ratio (POADR, defined as the number of people in age groups with life expectancies of 15 or fewer years, divided by the number of people at least 20 years old in age groups with life expectancies greater than 15 years). Effects of aging are evident in both measures, but when forecasted increases in life expectancy are taken into account, the POADR increases less rapidly than the OADR (see the table). Similar patterns are seen for many countries of the world (table S1).

Disability Adjustments

Disability-adjusted aging measures are another alternative [e.g., (Lafortune et al. 2007; Manton et al. 2006b)]. But consistent disability-adjusted aging measures from many countries have not previously appeared in the literature. To investigate the effects of disability, we define a measure analogous to OADR, the adult disability dependency ratio (ADDR, defined as the number of adults at least 20 years old with disabilities, divided by the number of adults at least 20 years without them) (see the table and table S1).

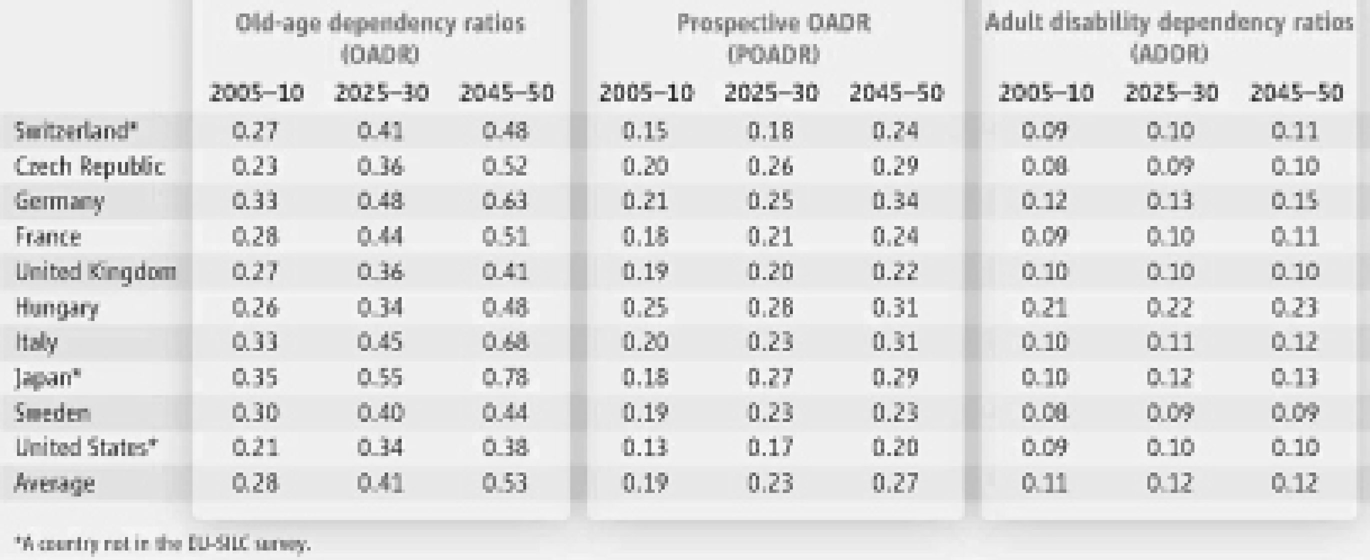
The OADRs increase much faster than the ADDRs. In the United Kingdom, for example, the OADR increases from 0.27 in 2005-10 to 0.36 in 2025-30 to 0.41 in 2045-50. In contrast, the ADDR stays constant at 0.10. Although the British population is getting older, it is also likely to be getting healthier, and these two effects offset one another. Not only does the ADDR increase less rapidly than the OADR, it also increases less rapidly than the POADR, so that adjusting for the likely future path of disability rates does not simply replicate the results of adjusting aging measures for changes in longevity.

In our forecasts for the United States, in 2003 the number of expected years of disability above age 65 is 4.1. This finding differs slightly from (Manton et al. 2006b), which forecast that figure to be 3.7 years in 2022. If the number of years of disability were forecast to change as in (Manton et al. 2006b), the increase in ADDRs would be even less.

Previous forecasts were made for years 2003 to 2030 of the number of people 65 and older with severe disabilities for 12 countries of the Organization for Economic Cooperation and Development (OECD) from data that were not harmonized across countries (Lafortune et al. 2007). Constant age- and sex-specific disability rates were applied to future populations, and the trend in age- and sex-specific disability rates between two recent surveys was extrapolated. However, age- and sex-specific dis- ability rates are changing, and trends between two surveys taken only a few years apart can be misleading, especially in the case of age- and sex-specific disability rates, because of the noisiness of those data.

Making consistent multicountry forecasts of the disability rates underlying the ADDR was difficult in the past. Data with a consistent measure of disability, harmonized across countries, were lacking. Data available for only one country, with disability-adjusted forecasts based on self-evaluated definitions of health, could reflect cultural specificity. The European Union Statistics on Income and Living Conditions survey (EU-SILC) survey now provides

Table 1. Dependency ratios. Authors' calculations. OADR and POADR are based on United Nations (2009b). ADDR based on (2009b) and (European Health Expectancy Monitoring Unit (EHEMU) 2009). The lower age boundary in all denominators is 20. See SOM §1 and tables S1 and S2 for more detailed methods and additional countries.



	Old-age dependency ratios (OADR)			Prospective OADR (POADR)			Adult disability dependency ratios (ADDR)		
	2005–10	2025–30	2045–50	2005–10	2025–30	2045–50	2005–10	2025–30	2045–50
Switzerland*	0.27	0.41	0.48	0.15	0.18	0.24	0.09	0.10	0.11
Czech Republic	0.23	0.36	0.52	0.20	0.26	0.29	0.08	0.09	0.10
Germany	0.33	0.48	0.63	0.21	0.25	0.34	0.12	0.13	0.15
France	0.28	0.44	0.51	0.18	0.21	0.24	0.09	0.10	0.11
United Kingdom	0.27	0.36	0.41	0.19	0.20	0.22	0.10	0.10	0.10
Hungary	0.26	0.34	0.48	0.25	0.28	0.31	0.21	0.22	0.23
Italy	0.33	0.45	0.68	0.20	0.23	0.31	0.10	0.11	0.12
Japan*	0.35	0.55	0.78	0.18	0.27	0.29	0.10	0.12	0.13
Sweden	0.30	0.40	0.44	0.19	0.23	0.23	0.08	0.09	0.09
United States*	0.21	0.34	0.38	0.13	0.17	0.20	0.09	0.10	0.10
Average	0.28	0.41	0.53	0.19	0.23	0.27	0.11	0.12	0.12

*A country not in the EU-SILC survey.

harmonized data on a specific definition of disability based on activity limitations [supporting online material (SOM) §2] for a large enough set of countries. A forecasting methodology was also needed that accounted for long-term relations between disability rates and mortality rates, and relations of disability rates across ages and sexes (SOM §1).

Even with the EU-SILC data, there are still problems. The EU-SILC could be biased if it systematically omits older people with dis- abilities. The survey does not include people in nursing homes (SOM §3.2 shows that this has little effect). In addition, we can currently only make disability-adjusted aging forecasts for high-income OECD countries, although we feel that this is sufficient to illustrate the potential advantages of the approach.

Better Tools for Policy-Making

Policy analysts long had little choice but to use aging forecast measures (e.g., published by the UN) based on chronological age. More recently, however, measures have been developed that do not assume that improvements in health and longevity will cease. These measures are not just different metrics for measuring the same thing. They measure different aspects of aging, ones in which biological and behavioral factors play a larger role. Other perspectives on aging are also possible, for example, in terms of prevalence of chronic diseases or of frailty, but these would also require new measures that are not based on chronological age.

The figures presented here are based on UN forecasts of survival rates. But populations are heterogeneous, and how this heterogeneity is treated influences how survival rates are forecast (Manton et al. 1986). Uncertainty in our forecasts comes primarily from two sources, (i) life- expectancy forecasts and (ii) disability rates that are conditional on those forecasts. But ADDRs are rather robust to differences in the speed of forecast life-expectancy changes and thus fairly insensitive to how heterogeneity is treated in making those forecasts (SOM §3.1). Use of ADDR could thus limit the scope for political speculation and controversy.

Such new measures of aging can help educate the public about likely consequences of improvements in health and longevity. Slow and predictable changes in pension age, for example, justified by an increased number of years of healthy life at older ages, may be more politically acceptable than large, abrupt changes justified on the basis of budgetary stringency. In 2000, the normal retirement age in the United States was 65. Today, it is 66; current legislation has it increasing to 67 in 2027 (U.S. Social Security Administration 2010); and it is likely to increase further to help avoid reductions in future pension payouts. In the United Kingdom, the normal pension age is scheduled to rise from 65 to 68 by 2044 (UK Government n.d.) and in Germany from 65 to 67 by 2031 (U.S. Social Security Administration n.d.). A change in U.S. legislation, for example, that would increase the normal pension age by one-half year for each year of additional life expectancy at age 65 would go a long way to ensuring the sustain- ability of Social Security payouts, even with- out further reforms. People who enjoy longer lives would finance part of their additional years of retirement themselves.

Population aging will certainly be the source of many challenges in coming decades. But there is no reason to exaggerate those challenges through mismeasurement. We will be able to address those problems better with a larger array of measures of aging, using those that are appropriate to the task at hand.

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Supplementary Information for “Remeasuring Aging“[1]

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Materials and Methods

Section 1: Computing the figures in Table 1 and Table S1

The data in Table 1 and Table S1 were computed using the following four steps.

Step 1: The estimation of the relation between disability-free life expectancy and unconditional life expectancy

The first step in our methodology is the estimation of the relation between disability-free life expectancy and unconditional life expectancy. Let

$$r_{a,s,c} = \frac{e^{df}_{a,s,c}}{e_{a,s,c}}$$

where e is life expectancy, e^{df} is disability free life expectancy, a is age, s is sex, and c refers to the country. The ratio is the fraction of person-years lived from age a onward that are free from disabilities. The numerators and denominators are calculated by European Health Expectancy Monitoring Unit (EHEMU, 2009) using data from European Union Income, Social Inclusion and Living Conditions survey (EU- SILC) data (UNICEF n.d.). The unconditional life expectancies in the denominators are extremely close to the life expectancies provided by the UN for the same time period.

Using ordinary least squares, we estimate a simple linear specification that makes the r's a function of age, sex, and country-specific dummy variables.

$$log\left(\frac{r_{a,s,c}}{l-r_{a,s,c}}\right) = \beta_0 + \beta_1 a^2 + \beta_2 D_f + \sum_{c=2}^{17} \chi_c D_c + \sum_{c=2}^{17} \delta_c D_c D_f + \varepsilon_{a,s,c} \qquad \text{(S1)}$$

where the β's, χ’s, and δ's are parameters to be estimated, D_f is a dummy variable for females, D_c's are country-specific dummy variables, and ε is an independently distributed normally distributed random error term. We used data for 5-year intervals from age 30 to 85+, 17 high-income OECD countries, and usually for three years, 2005-2007 (European Health Expectancy Monitoring Unit (EHEMU) 2009). These countries are listed in Table S1. All told, we have 1200 observations, and our regression has 1165 degrees of freedom. We investigated using age, as well as the square of age in the regression, but the linear term was statistically insignificant, substantively insignificant, and had virtually no effect on the fit of the model to the data.

The estimated coefficients are shown in Table S2. The model fits the data quite well. The implication of this specification is that the rates of disabilities generally would decrease as life expectancies increase. This is generally consistent with observations on developed countries with at least a comparable decade long data series (Lafortune et al. 2007; Crimmins et al. 2009; Manton et al. 2006).

Step 2: Forecasting disability free life expectancies

We use UN forecasts of life expectancies by age, sex, and country for 5-year periods from 2005-2010 to 2045-50 (United Nations 2009b) and equation (S1) to forecast disability free life expectancies by age, sex, and country for those time periods.

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[1] published online on the website of *Nature*,

$$\hat{e}^{df}_{a,s,c} = e^{UN}_{a,s,c}\hat{r}_{a,s,c} \qquad \text{(S2)}$$

where $e^{UN}_{a,s,c}$ are age-, sex- and country-specific life expectancies forecasted by the UN and a caret (^) over a variable indicates it is our forecasted value.

Step 3: Computing disability rates from disability free and unconditional life expectancies

Given the disability free life expectancies in equation (S2) and UN life tables, we can compute the prevalence of disabilities in each 5-year age group by working sequentially from the oldest age group, 85+, to the youngest, 30-34.

Using standard life table notation, we know that

$$\hat{T}^{df}_{85+,s,c} = \hat{e}^{df}_{85+,s,c} l^{UN}_{85+,s,c} \qquad \text{(S3)}$$

where $\hat{T}^{df}_{85+,s,c}$ (and $\hat{L}^{df}_{85+,s,c}$) is the forecasted number of person-years lived from age 85 onwards without disabilities and $l^{UN}_{85+,s,c}$ is the number of people in the forecasted UN life table who have survived to exact age 85.

The proportion of people at age 85+ without disabilities can now be expressed as:

$$\hat{\pi}^{df}_{85+,s,c} = \frac{\hat{T}^{df}_{85+,s,c}}{\hat{T}^{UN}_{85+,s,c}} = \frac{\hat{L}^{df}_{85+,s,c}}{\hat{L}^{UN}_{85+,s,c}} \qquad \text{(S4)}$$

Working our way up the age range, we have:

$$\hat{L}^{df}_{80,s,c} = \hat{e}^{df}_{80,s,c} l^{UN}_{80,s,c} - \hat{T}^{df}_{85+,s,c} \qquad \text{(S5)}$$

and

$$\hat{\pi}^{df}_{80+,s,c} = \frac{\hat{L}^{df}_{80,s,c}}{\hat{L}^{UN}_{80,s,c}}$$

where $\hat{L}^{df}_{80,s,c}$ is the number of person-years lived between age 80 and 85 without disabilities.

We can continue working our way down the age distribution in this way, using information derived from later ages to compute proportions without disabilities at earlier ones.

Step 4: Creating the numbers in Table S1

The ADDRs in Tables 1 and S1 were computed from the $\hat{\pi}$'s and UN age distributions (United Nations 2009b). The OADRs were computed from UN age distributions.

Section 2: The Data

We use two sources of data, age- and sex-specific life expectancies without disabilities from EU-SILC for 17 countries (European Health Expectancy Monitoring Unit (EHEMU) 2009) and age- and sex-specific life expectancies, forecasted by the United Nations. The countries are Austria, Belgium, Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Portugal, Slovakia, Spain, Sweden, and the United Kingdom. These are all the high-income OECD countries that are included in the EU-SILC survey with the exception of Denmark, where two response categories were used to assess long-term activity limitation (yes; no) compared to three levels in all other countries (severely limited; limited but not severely; none).

Regardless of the heterogeneity within this group of countries, we found that the shapes of relations between age- and sex-specific ratios of life expectancies without disabilities to unconditional life expectancies were very similar to one another. The levels of those ratios, however, did differ across countries and these differences were captured in the country-specific dummy variables. Using the procedure indicated in the Notes to Table S1, we have extended the forecasts of disabilities to all high- income OECD countries.

The survey question in the EU-SILC (PH030) asks about activity limitations due to health problems. It makes no distinction between physical and mental health. Activity limitations are subjectively assessed on the basis of what people usually do. An activity limitation is only included if it persisted for half a year or more. The EU-SILC survey allowed only three answers to the question whether the individual has any activity limitations. In English, these are: (i) “no, not limited”, (ii) “yes, limited”, and (iii) “yes, strongly limited”.

In this paper, when we refer to disabilities, we are talking about the proportions of people who respond that they are “strongly limited.” We use only these responses because the category of being “limited” is less definitive. The combination of an unclear definition of what “limited” means, different translations of the survey question, and different cultures can cause the resulting data to be noisy.

Currently, the EU-SILC survey is the best source of disability data comparable across countries. Because EU-SILC data are used for a variety of policy purposes, care has been taken to make the questionnaires as similar as possible in all EU countries. In all EU countries, except Denmark, the EU-SILC survey was administered on a face-to-face basis. Although older people may not be able to answer some questions – for example, when asked the value of their home – they are likely to be able to tell interviewers who are sitting beside them whether or not they are limited in things that people normally do.

There are several important features of this definition of disability to keep in mind. First, the people who answer that they are “strongly limited” are not just those who are near the end of their lives. For example, they could be strongly limited because they have difficulties with mobility or because they have difficulty with household chores due to arthritis. Second, the limiting condition must be persistent. If it did not persist for 6 months or more, it is not counted as a disability. Third, this definition includes both physical and mental problems. To put this in perspective, around 13 percent of UK females 60-64 were disabled in 2007.

Disability status in the EU-SILC survey depends on one’s physical and mental health and on the environment, broadly defined, in which the individual lives. It is a hybrid bio-social measure. Slow moving trends in disability can be due to improvements in biological functioning, a change in the environment that makes activities easier to perform, a change in the norms concerning normal functioning, or some combination of these. In this paper, we make forecasts of disability rates for high- income OECD countries up to 2048, and the trends in Old Age Dependency Ratios and Adult Disability Dependency Ratios are dramatically different. Our key assumption is that the age- and sex-specific ratios of disability-free life expectancies to unconditional life expectancies can be specified as in equation S1 above. By linking disabilities to life expectancies, we are emphasizing the biological side of disabilities. Essentially, we are holding the social environment and cultural norms constant. Changes in our forecasted disability rates are only those associated with changes in life expectancies.

Publicly available data on disabilities from SILC come in the form of age-specific, disability-free life expectancies. These are produced using the Sullivan method (Sullivan 1971), in which age-specific disability rates are combined with existing life tables. Similar measures using the Sullivan method are widely available, but they are derived from a variety of questions about health or activity limitations (Robine et al. 2006). With the EU-SILC, there are now enough comparable data to find regularities that can be used in forecasting (Jagger et al. 2008).

The United Nations publishes the most widely used national level demographic forecasts. These are based on forecasts of fertility, mortality, and migration. The UN publishes the life tables (United Nations 2009a) used in making those forecasts and these are the life tables that we use in this paper. There is a great deal of historical data on the evolution of age- and sex-specific survival rates and this makes the forecasting of their joint evolution over time easier. Nevertheless, there is still some controversy over the path of future survival rate changes (Lutz et al. 2004). The UN takes a middle path between the competing possibilities and assumes that in the future the speed of life expectancy changes in today's richer countries will be slower than it has been in the recent past, although evidence from this decade does not indicate any slowing (Christensen et al. 2009). The methodology that we present here is not dependent on the UN life tables and can easily be used with alternative mortality forecasts (see Section 3 for an analysis of the effects of different mortality change assumptions).

Section 3: Sensitivity Analyses

3.1 Sensitivity of ADDR to Alternative Life Expectancy Forecasts

The forecasts presented in Tables 1 and S1 are based on UN population and mortality rate forecasts. The UN mortality rate forecasts assume a slowing down in the speed of life expectancy improvement that is not evident in the data (Christensen et al. 2009). In the European Demographic Data Sheet (Ediev et al. 2008) forecasts of European populations to 2030 were based, in part, on the assumption that the pace of life expectancy increases would not diminish (Mamolo & Scherbov 2009). Here, we extended the forecasts for the United Kingdom to 2050. The forecasts in the European Demographic Data Sheet differ slightly from those of the UN, but for the measures presented in the Table S3, the only difference that matters is the difference in the speed of life expectancy increases and, as a consequence, the number of people in older ages.

Table S3 shows changes in the old age dependency rate (OADR) and the adult disability dependency rate (ADDR) for the United Kingdom using forecasts made by the UN and in the European Demographic Data Sheet (extended to 2050). For men in the UK, the forecasted increase in disability-free life expectancy at age 65 between 2005-2010 and 2045-50 would be 2.46 years from the UN life tables and 4.15 years if we use the assumption that life-expectancy increases would not slow down. The analogous figures for women are 2.80 years and 4.43 years, respectively.

Increases in the speed of life expectancy improvement, naturally, cause the conventional old age dependency ratio to rise more rapidly. This is not the case, however, when we look at our new adult disability dependency ratio (ADDR). The ADDR is much more robust to differences in future mortality rate forecasts. Increases in the number of older people due to lower mortality rates are compensated, almost perfectly in the case of the UK, by changes in age-specific rates of disabilities.

Not all measures are equally sensitive to the uncertainties inherent in mortality rate forecasts. Some measures, such as disability-free life expectancies at various ages, are quite sensitive. But measures where the effects of life expectancy changes are offsetting, such as the ADDR, are much more robust. This makes the ADDR especially useful for policy analysis.

Section 3.2: Sensitivity of ADDR to the Inclusion of Elderly in Nursing Homes

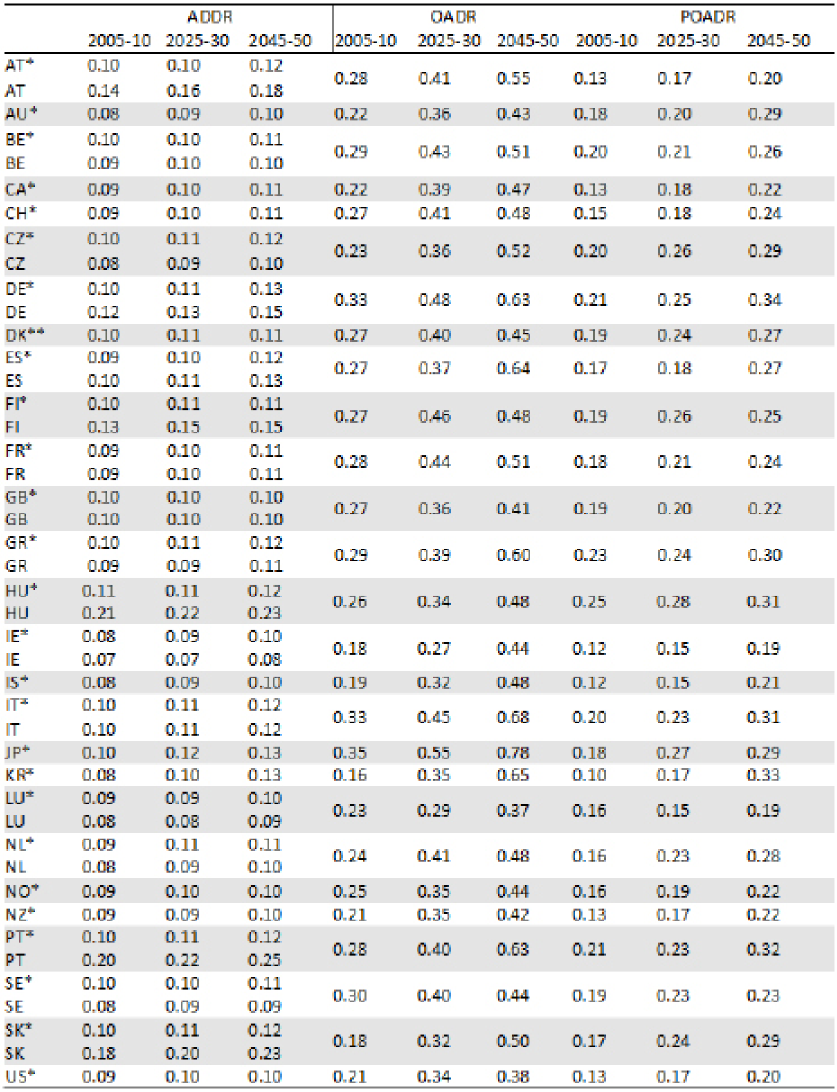
The EU-SILC survey does not cover people living in institutions such as nursing homes. Because people living in nursing homes are typically disabled according to our definition, their omission results in a downward bias in ADDR, one that potentially grows over time as populations age. In order to test the sensitivity of our results to the presence of this bias, we collected data on proportions of elderly populations in nursing homes by sex and by 5-year age groups from 60-64 to 80+. Eurostat provides these data for 13 of the 17 high-income OECD countries that we use in our statistical analysis for 2001 (European Commission 2002).

To test for the importance of the exclusion of the elderly in nursing homes, we assumed that 100 percent of the elderly in nursing homes were disabled, kept the sex- and age-specific proportions of populations above the age of 60 constant, and adjusted our forecasted sex- and age-specific disability rates accordingly. These adjusted sex- and age-specific disability rates were then used to recalculate our ADDRs. The results are shown in Table S4.

There are four important features of Table S4. First, the downward bias in the data for 2008 is very small. For example, the adjusted ADDR for Austrian men was 0.1221 and the unadjusted figure was 0.1216. In all 13 countries in our table and for both sexes, the differences between the adjusted and unadjusted figures in 2008 are relatively small. Second, although the downward bias does grow over time, it is still relatively small in 2048. For example, the adjusted ADDR for Austrian men is 0.1524 and the unadjusted figure is 0.1481. Although the speed of change of the adjusted ADDR is very slightly higher for the adjusted ADDR compared to the unadjusted ADDR, both speeds are different from the speed at which the OADR changes. – The final point is the most important. In this paper, we argue that we need new measures of aging that are not solely based on chronological age. The speed of change of the unadjusted ADDR is much smaller than the speed of change of the OADR. Because the differences between the adjusted and adjusted ADDRs are so small, this result statement is also true for the adjusted ADDRs. In other words, although the EU-SILC data do not include people in nursing homes, our main conclusion about the importance of adjusting aging measures for changes in disability rates still stands.

Supplementary Tables

Table S1. Forecasts of adult disability dependency ratios, old age dependency ratios, and prospective old age dependency ratios. ADDR is the ratio of the number of people 20+ years old with disabilities to the number of people 20+ years old without disabilities. OADR is the ratio of the number of people 65+ years old to the number of people 20 to 64 years old. POADR is the number of people in age groups with life expectancies of 15 or fewer years, divided by the number of people at least 20 years old in age groups with life expectancies greater than 15 years. Abbreviations: AU, Australia; AT, Austria; BE, Belgium; CA, Canada; CH, Switzerland; CZ, Czech Republic; DE, Germany; DK, Denmark; ES, Spain; FI, Finland; FR, France; GB, United Kingdom; HU, Hungary; IE, Ireland; IS, Iceland; IT, Italy; JP, Japan; KR, Republic of Korea; LU, Luxembourg; NL, Netherlands; NO, Norway; NZ, New Zealand; PT, Portugal; SE, Sweden; SK, Slovakia; and US, United States. Authors' calculations



	ADDR			OADR			POADR		
	2005-10	2025-30	2045-50	2005-10	2025-30	2045-50	2005-10	2025-30	2045-50
AT*	0.10	0.10	0.12	0.28	0.41	0.55	0.13	0.17	0.20
AT	0.14	0.16	0.18						
AU*	0.08	0.09	0.10	0.22	0.36	0.43	0.18	0.20	0.29
BE*	0.10	0.10	0.11	0.29	0.43	0.51	0.20	0.21	0.26
BE	0.09	0.10	0.10						
CA*	0.09	0.10	0.11	0.22	0.39	0.47	0.13	0.18	0.22
CH*	0.09	0.10	0.11	0.27	0.41	0.48	0.15	0.18	0.24
CZ*	0.10	0.11	0.12	0.23	0.36	0.52	0.20	0.26	0.29
CZ	0.08	0.09	0.10						
DE*	0.10	0.11	0.13	0.33	0.48	0.63	0.21	0.25	0.34
DE	0.12	0.13	0.15						
DK**	0.10	0.11	0.11	0.27	0.40	0.45	0.19	0.24	0.27
ES*	0.09	0.10	0.12	0.27	0.37	0.64	0.17	0.18	0.27
ES	0.10	0.11	0.13						
FI*	0.10	0.11	0.11	0.27	0.46	0.48	0.19	0.26	0.25
FI	0.13	0.15	0.15						
FR*	0.09	0.10	0.11	0.28	0.44	0.51	0.18	0.21	0.24
FR	0.09	0.10	0.11						
GB*	0.10	0.10	0.10	0.27	0.36	0.41	0.19	0.20	0.22
GB	0.10	0.10	0.10						
GR*	0.10	0.11	0.12	0.29	0.39	0.60	0.23	0.24	0.30
GR	0.09	0.09	0.11						
HU*	0.11	0.11	0.12	0.26	0.34	0.48	0.25	0.28	0.31
HU	0.21	0.22	0.23						
IE*	0.08	0.09	0.10	0.18	0.27	0.44	0.12	0.15	0.19
IE	0.07	0.07	0.08						
IS*	0.08	0.09	0.10	0.19	0.32	0.48	0.12	0.15	0.21
IT*	0.10	0.11	0.12	0.33	0.45	0.68	0.20	0.23	0.31
IT	0.10	0.11	0.12						
JP*	0.10	0.12	0.13	0.35	0.55	0.78	0.18	0.27	0.29
KR*	0.08	0.10	0.13	0.16	0.35	0.65	0.10	0.17	0.33
LU*	0.09	0.09	0.10	0.23	0.29	0.37	0.16	0.15	0.19
LU	0.08	0.08	0.09						
NL*	0.09	0.11	0.11	0.24	0.41	0.48	0.16	0.23	0.28
NL	0.08	0.09	0.10						
NO*	0.09	0.10	0.10	0.25	0.35	0.44	0.16	0.19	0.22
NZ*	0.09	0.09	0.10	0.21	0.35	0.42	0.13	0.17	0.22
PT*	0.10	0.11	0.12	0.28	0.40	0.63	0.21	0.23	0.32
PT	0.20	0.22	0.25						
SE*	0.10	0.10	0.11	0.30	0.40	0.44	0.19	0.23	0.23
SE	0.08	0.09	0.09						
SK*	0.10	0.11	0.12	0.18	0.32	0.50	0.17	0.24	0.29
SK	0.18	0.20	0.23						
US*	0.09	0.10	0.10	0.21	0.34	0.38	0.13	0.17	0.20

* Disability rates used in these ADDR calculations were computed using the relationship between disability free life expectancies and unconditional life expectancies estimated for Italy (see Table S2). The three coefficients that we used are the constant term, the dummy for Italy, and the dummy for the country-gender interaction. Italy is the country with coefficients closest to the median values across all the countries in the sample. When using the Italian coefficients to calculate ADDRs based on UN data (United Nations 2009b), the levels are different than in cases when we used the countries' own coefficients (Table S2), based on EU-SILC data (European Health Expectancy Monitoring Unit (EHEMU) 2009). Importantly, each country's changes over time are very similar regardless of which coefficients are used. This allows us to use the Italian coefficients to estimate changes over time for countries not in the EU-SILC survey, even though the levels for those countries should be interpreted with caution. The use of the Italian coefficients serves as a standard. We expect that it removes idiosyncratic and culture-specific differences in the reporting of disability rates. This allows us to make cross-country comparisons based only on age structure and life expectancy differences.

** Denmark is a EU-SILC country, but it was omitted from the estimation because of data incompatibility due to some differences in the question used in the Danish SILC. It is treated here as a non-EU-SILC country OADRs and POADRs are calculated using data from United Nations (2009b).

Table S2. Regression results. All calculations were done with the R statistical software. Data for this regression analysis are from (European Health Expectancy Monitoring Unit (EHEMU) 2009). Residual standard error: 0.176 on 1165 degrees of freedom Multiple R-Squared: 0.914. F-statistic: 362 on 34 and 1165 DF, P-value: <2e-16. Omitted country dummy is for Austria. The value for Austria is the constant term, and the coefficients indicate the difference between the country's value and Austria's. In the table, "e" should be interpreted as "times 10 to the power of," e.g., "1.21e-01" should be interpreted as "1.21 times 10 to the power of -1."

Statistical significance codes - ranges for Pr(>|t|): 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '†' 1. If the coefficient is not statistically significant at the 10 percent level, there is no symbol following the number in the column headed Pr(>|t|).

	Estimate	**Std. Error**	***t* value *Pr*(>|*t*|)**
Intercept	2.06e+00	2.69e-02	76.55 < 2e-16 ***
Age squared	-2.26e-04	3.45e-06	-65.51 < 2e-16 ***
Women	-2.99e-01	3.34e-02	-8.95 < 2e-16 ***
Country Dummies			
Belgium	5.10e-01	3.42e-02	14.92 < 2e-16 ***
Czech Republic	6.23e-01	4.06e-02	15.36 < 2e-16 ***
Finland	5.31e-02	3.37e-02	1.57 0.11584
France	3.69e-01	3.03e-02	12.19 < 2e-16 ***
Germany	3.74e-01	3.37e-02	11.08 < 2e-16 ***
Greece	4.43e-01	2.74e-02	16.20 < 2e-16 ***
Hungary	-3.37e-01	3.18e-02	-10.60 < 2e-16 ***
Ireland	5.30e-01	3.73e-02	14.21 < 2e-16 ***
Italy	3.89e-01	4.18e-02	9.30 < 2e-16 ***
Luxembourg	4.30e-01	3.86e-02	11.13 < 2e-16 ***
Netherlands	3.93e-01	3.52e-02	11.16 < 2e-16 ***
Portugal	-1.71e-01	3.27e-02	-5.23 2.1e-07 ***
Slovakia	-2.02e-01	3.34e-02	-6.05 1.9e-09 ***
Spain	3.47e-01	2.78e-02	12.51 < 2e-16 ***
Sweden	5.95e-01	5.73e-02	10.38 < 2e-16 ***
United Kingdom	3.58e-01	3.03e-02	11.79 < 2e-16 ***
Country-sex interactions			
Belgium:*Women	-5.01e-02	5.16e-02	-0.97 0.33220
Czech Republic:*Women	-8.40e-02	5.29e-02	-1.59 0.11239
Finland:*Women	8.33e-02	5.04e-02	1.65 0.09878†
France:*Women	9.90e-02	4.09e-02	2.42 0.01556 *
Germany:*Women	-1.89e-01	4.99e-02	-3.79 0.00016 ***
Greece:*Women	1.69e-01	3.92e-02	4.32 1.7e-05 ***
Hungary:*Women	1.07e-01	4.13e-02	2.60 0.00948 **
Ireland:*Women	1.57e-01	4.53e-02	3.47 0.00054 ***
Italy:*Women	2.68e-02	5.47e-02	0.49 0.62413
Luxembourg:*Women	9.39e-02	8.84e-02	1.06 0.28849
Netherlands:*Women	3.00e-01	5.74e-02	5.23 2.1e-07 ***
Portugal:*Women	-1.90e-01	4.41e-02	-4.31 1.8e-05 ***
Slovakia:*Women	-4.44e-02	5.34e-02	-0.83 0.40576
Spain:*Women	-7.11e-02	3.85e-02	-1.85 0.06486†
Sweden:*Women	1.63e-02	8.86e-02	-0.18 0.85376
United Kingdom:*Women	1.21e-01	4.20e-02	2.87 0.00413 **

Table S3. Old Age Dependency Rates and Adult Disability Dependency Rates for the UK. Abbreviations: ADDR - Adult Disability Dependency Ratio, OADR - Old Age Dependency Ratio, EDDS - European Demographic Datasheet, UN - United Nations. Note: ADDR computations for 2005-10 refer to data collected for the year 2008. We put this in the middle of the 2005-10 interval for compatibility with the UN. Figures above computed using EDDS and UN assumptions differ slightly for 2005-10 because of slight differences in initial age structures. The age structures used in the EDDS calculations come from Eurostat. The age structures for the UN calculations come from United Nations (2009b). These are very slightly different.

Sources: EDDS data are from Ediev et al. (2008). Readers can learn about the assumptions made therein (Mamolo & Scherbov 2009). UN data are from United Nations (2009b), which also contains the assumptions used in UN forecasts.

	2005-10	2025-30	2045-50
ADDR – EDDS assumptions	0.096	0.099	0.104
ADDR – UN assumptions	0.098	0.101	0.104
OADR – EDDS assumptions	0.269	0.383	0.496
OADR – UN assumptions	0.273	0.356	0.406

Table S4. Adult Disability Dependency Rates (ADDRs) Adjusted for the Inclusion of the Nursing Home Population, Unadjusted, and Old Age Dependency Rates. (A)For 13 EU Countries, 2008 and 2048, shows ADDRs for countries for which we had nursing home data from (European Commission 2002). (B) Shows OADRs for the same countries. There were computed as in Table S1.Source: Same as Table S1 with data on nursing homes from (European Commission 2002).

(A)

	ADDR,men				ADDR,women			
	Unadjusted		Adjusted		Unadjusted		Adjusted	
Country	2008	2048	2008	2048	2008	2048	2008	2048
Austria	0.121	0.148	0.122	0.152	0.168	0.203	0.173	0.213
Belgium	0.075	0.086	0.078	0.092	0.107	0.122	0.115	0.141
Finland	0.120	0.134	0.121	0.136	0.149	0.170	0.151	0.177
France	0.084	0.096	0.087	0.103	0.100	0.122	0.106	0.139
Greece	0.080	0.098	0.081	0.099	0.092	0.113	0.093	0.116
Ireland	0.063	0.076	0.064	0.080	0.069	0.085	0.072	0.094
Italy	0.085	0.106	0.086	0.108	0.113	0.142	0.115	0.149
Luxembourg	0.075	0.081	0.076	0.084	0.091	0.097	0.097	0.108
Netherlands	0.080	0.096	0.081	0.102	0.080	0.098	0.085	0.114
Portugal	0.152	0.184	0.154	0.190	0.245	0.307	0.249	0.319
Slovakia	0.152	0.185	0.154	0.188	0.211	0.266	0.214	0.272
Spain	0.083	0.105	0.084	0.107	0.119	0.152	0.121	0.157
UnitedKingdom	0.087	0.092	0.088	0.093	0.104	0.112	0.107	0.117

(B)

	OADR,men		OADR,women	
Country	2008	2048	2008	2048
Austria	0.225	0.493	0.325	0.613
Belgium	0.239	0.444	0.337	0.571
Finland	0.221	0.412	0.327	0.554
France	0.234	0.440	0.328	0.593
Greece	0.256	0.539	0.326	0.673
Ireland	0.158	0.391	0.202	0.481
Italy	0.274	0.588	0.385	0.770
Luxembourg	0.188	0.329	0.267	0.407
Netherlands	0.206	0.430	0.275	0.540
Portugal	0.238	0.541	0.327	0.720
Slovakia	0.137	0.412	0.229	0.594
Spain	0.225	0.581	0.311	0.703

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The Characteristics Approach to the Measurement of Population Aging[1]

Warren C. Sanderson and Sergei Scherbov

Most studies of population aging focus on only one characteristic of people: their chronological age. This is the case, for instance, in the UN's reference volume, *World Population Ageing, 1950–2050* (United Nations 2001). The implicit assumption is that other characteristics relevant to population aging do not change over time and place. But clearly, they do. To take an obvious ex- ample, 65-year-olds today generally have higher remaining life expectancies and are healthier than their counterparts in earlier generations – reflected, in many countries, in rising ages of eligibility for public pensions (Christensen et al. 2009; McLaughlin et al. 2012; OECD 2012). Many important characteristics of people vary with age, but age-specific characteristics also vary over time and differ from place to place. Focusing on a single aspect of the changes entailed in population aging but not on all the others provides a limited picture of the process, one that is often not appropriate for either scientific study or policy analysis.

A small part of the large and growing literature on population aging has taken a broader view of the process, considering characteristics of people beyond their chronological age: remaining life expectancy, health and morbidity, disability rates, and cognitive functioning. It begins with Ryder (1975). Ryder wrote (p. 16):

> To the extent that our concern with age is what it signifies about the degree of deterioration and dependence, it would seem sensible to consider the measurement of age not in terms of years elapsed since birth but rather in terms of the number of years remaining until death.…
>
> We propose that some arbitrary length of time, such as 10 years, be selected and that we determine at what age the expectation of life is 10 years, that age to be considered the point of entry into old age.…

Ryder used this definition of the threshold of old age to tabulate those entry ages for the Coale-Demeny "West" family of model life tables (Coale & Demeny 1966). In addition, he computed the proportions old, under his definition, for a variety of model stable populations.

The importance of Ryder's reasoning was realized only slowly. Ryder himself made no further use of it, and the next paper that applied it came almost a decade later. Two reasons might explain the delay. First, Ryder's discussion appeared in an article about stable populations, not about aging. Aging was not a topic of much interest to the demographic community at the time, when the major policy concern was rapid population growth in less developed countries. When concern about population aging began to increase, Ryder's research on stable populations was not an obvious reference. Second, Ryder's interest seemed limited to defining a more meaningful threshold of old age. For many demographers this was not a pressing issue. The convention that people became elderly at age 65 seemed both simple and sensible. In essence, Ryder was providing an answer to a question that almost no one was asking.

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Siegel and Davidson (1984) were the first to apply Ryder's proposal to actual data. They used two durations of remaining life expectancy, 10 and 15 years, to define ages at which old age began for the United States in census years from 1920 to 1980. Like Ryder, they computed proportions of the population that were "old" according to those definitions. (Interestingly, the proportion old was the same in 1980 as it was in 1940.) Siegel and Davidson also realized that remaining life expectancy as a characteristic could be used for more than defining the old-age threshold. They suggested that it could also be used in the design of government programs, such as, in the United States, in indexing the age for receiving a full Social Security pension.

When we wrote Sanderson and Scherbov (2005), we were unaware of this previous literature. In that article, we pointed out that age could be computed both backwards, as the number of previous birthdays, and forwards, based on remaining life expectancy. We used our forward-looking age to compute what we subsequently called prospective age, which is chronological age adjusted for changes in life expectancies. We used this to introduce a new indicator of aging, the *prospective median age*. We also presented a new version of the conventional old-age dependency ratio, where the threshold ages at the beginning and the end of the working-age period were adjusted for changes in life expectancies. Determining the prospective median age is different in an important way from the calculations of Ryder and Siegel and Davidson. In both of those earlier studies, the level of a characteristic was chosen and this determined a series of ages associated with that level. For the prospective median age, there is no fi level of a characteristic that can be used.

Ideas similar to ours were independently arrived at by Shoven (2007). The intellectual ancestor of Shoven (2007) – and the related articles, Shoven (2008) and Shoven and Goda (2010) – was not the demographer Norman Ryder but the economist Victor Fuchs. Fuchs (1984) was interested in the proportion of the population that was elderly. He tabulated data for the US using three different definitions: (1) the proportion of the population 65+, the proportion of the population 65+ who would die in the succeeding five years, and (3) the proportion of the population 65+ who are not in the labor force. Definitions (2) and (3) supplement chronological age with characteristics of people that change over time.

The Siegel and Davidson estimates of proportions elderly in the United States have been updated (Siegel 1993; Siegel 2012). Other than in these publications, Ryder's ideas about age and aging remained unused until Heigl (2002) proposed an interesting application. Heigl wanted to obtain a quantitative measure of the changes over time in the active life expectancy of the elderly. To do this, he used Ryder's threshold age for becoming elderly and computed active life expectancy from that age forward. Heigl was the first to propose a measure that combined two time-varying age-specific characteristics. However, according to the *Web of Science* (Thompson Reuters n.d.), Heigl's article, which was written in German, has up to now never been cited.

Although there have been further developments (Lutz et al. 2008; Sanderson & Scherbov 2007; Sanderson & Scherbov 2010), the methodology still lacks a name, a formal set of equations and definitions, and awareness that the literature taken together can be seen as forming a new paradigm in conceptualizing population aging. We call it the *characteristics approach*. With the growing interest in aging populations and in policies toward them, we believe this approach may prove to be especially useful.

Characteristic-based measures of age

Let $C_t(\alpha)$ be a schedule of some characteristic relevant to the study of population aging (such as remaining life expectancy), giving the values of the characteristic at each chronological age α. The schedule is allowed to vary over time. If $C_t(\alpha)$ is continuous and monotonic in α, it can be inverted to obtain the schedule of chronological ages associated with each particular value of the characteristic at time t. We call these α-ages.

Most directly, α-ages can be calculated from the inverse of the characteristics schedule. Thus the chronological age $\alpha_{\kappa,t}$ at which the level of a specified characteristic is κ at time t would be given by

$$\alpha_{\kappa,t} = C_t^{-1}(\kappa_t), \tag{1}$$

where C_t^{-1} is the characteristic schedule at time t. In the simplest case the level of the characteristic does not change over time, so that κ has no t subscript. For example, if the time-invariant characteristic was a remaining life expectancy of 15 years, the α-age – the age at which that remaining life expectancy was attained – for Americans (average of both sexes) in 2010 is found to be 71 years and 1 month. We call the α-ages based on invariant characteristics *constant characteristic ages*.

The characteristics approach to the measurement of population aging includes the conventional measure of chronological age but is far more general. For concreteness, we focus on four characteristics: (1) chronological age, (2) remaining life expectancy, (3) the mortality rate, and (4) the proportion of adult person-years lived after a particular age. (The same approach allows the use of many other characteristics as well.) Each of these characteristics has a particular interpretation for the study of population aging. Chronological age is included both to show how conventional measures can be naturally embedded in the generalized framework and to provide a quantitative benchmark against which to assess the importance of including other characteristics. Remaining life expectancy is included because it can be used to produce a forward-looking definition of age. The mortality rate is included because it can be used as a rough but easily measurable ordinal indicator of the health of a group of older people. Finally, we include the proportion of adult person-years lived after a given age because it can be used to construct a simple hypothetical demographically indexed public pension system.

We use those four characteristics to provide a perspective on an age-old question: how old do you need to be to be considered “old”? In this case, the α-age at which people make the transition into the category “old” generally varies over time. We call the resulting trajectories “transition trajectories” – one for each of the four characteristics. Ryder (1975) and Siegel and Davidson (1984) computed transition trajectories on the basis of remaining life expectancy.

A health-based characteristic could also be used to mark the entrance to old age. Health is a complex quality, but a rough and readily accessible measure of it would be to associate population health at each given age with the level of the corresponding age-specific mortality rate. In this case, α-ages based on the life-table mortality rate m_x would provide ages of comparable population health across space and time (Cutler et al. 2007; Fuchs 1984; Vaupel 2010) and could also be used to mark the transition to old age.

Another important transition is the one at which people become eligible for a full public pension. Pension systems become unsustainable if eligibility ages are fixed while life expectancy steadily rises. α-ages allow us to specify a simple alternative public pension system where the fraction of adult person- years spent eligible for a pension remains constant. Such a system is equitable in the sense that the ratio of years of pension to years in the working ages remains fixed, even as life expectancy changes. We call the ratio of person-years lived at age x and beyond to the number of person-years lived from age $20, T_x/T_{20}$ in life-table notation, the "life-course ratio" because it allows fruitful links to life-course studies (Lee & Goldstein 2003). In the special case where the life-course ratio is equal to the proportion of adult person- years in which people are eligible for a pension in a specific base year, the corresponding α-age provides an easily understood measure that defines the age at pension eligibility and can therefore be used to inform discussions of pension age changes.

In Figure 1, we show the α-age transition trajectories for the onset of old age in four countries that have experienced significant aging – West Germany, Japan, Russia, and the United States – using the four illustrative characteristics. To facilitate comparison, we set the values of the characteristics at the levels observed for 65-year-olds in each country in 1965. The standardization highlights the comparative trends in the transition trajectories across the four countries.

In each country panel in Figure 1 we show the three α-age transition trajectories and a horizontal line for age 65. By construction, all four lines coincide at age 65 in 1965. The α-age e_x transition trajectory shows the chronological ages that had the same remaining life expectancies as observed in the country at age 65 in 1965. The α-age m_x transition trajectory shows the chronological ages at which people had the same single-year mortality rate as was observed in the country at age 65 in 1965. The α-age T_x/T_{20} transition trajectory does the same thing for the life-course ratio.

Two features of the chart are evident. First, Russia has had a pattern of aging distinctly different from those of the other three countries. Instead of having rising ages at the transition to old age after 1970, it has fluctuating α-ages with no clear trend. With little improvement in survivorship at older ages, the onset of old age did not change much. Russia's experience is similar to that of many other Eastern European countries. Second, since 1970 in the other three countries, the m_x-based α-age rises faster than the ages for the other two characteristics, and the α-age based on the life-course ratio rises the most slowly. For example, keeping the α-age constant in the United States would have meant that the age at eligibility for a full public pension would have risen at a rate of about 1.3 months per year over the period 1965-2010. A constant α-age pension reform in the US that began in 1965 would have brought the pensionable age to 69.8 by 2007. In comparison, using the m_x-based α-age, we can see from the chart that people 73.4 years old in 2007 would be as healthy as 65-year-olds in 1965. Therefore, people who retired at age 70 in 2007 would be healthier than people who retired at age 65 in 1965. A similar pattern can be seen for West Germany and Japan, indicating that initial retirees under our simple pension rule would have become, on average, healthier over time.2

Characteristics-based measures of population aging

In the conventional framework, age itself is not an object of study. If people have always grown old at age 65 and if they will always grow old at age 65 in the future, there is nothing to study. The age at the onset of old age is fixed forever. However, if our interest is in the

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2 For analogous calculations of α-age trajectories for other characteristics of population aging, see Shoven and Goda (2010); Siegel (2012); and Cutler et al. (2007). For cases where the level of the characteristic is changing over time, see Sanderson and Scherbov (2005); Lutz, Sanderson, and Scherbov (2008); and Sanderson and Scherbov (2008).

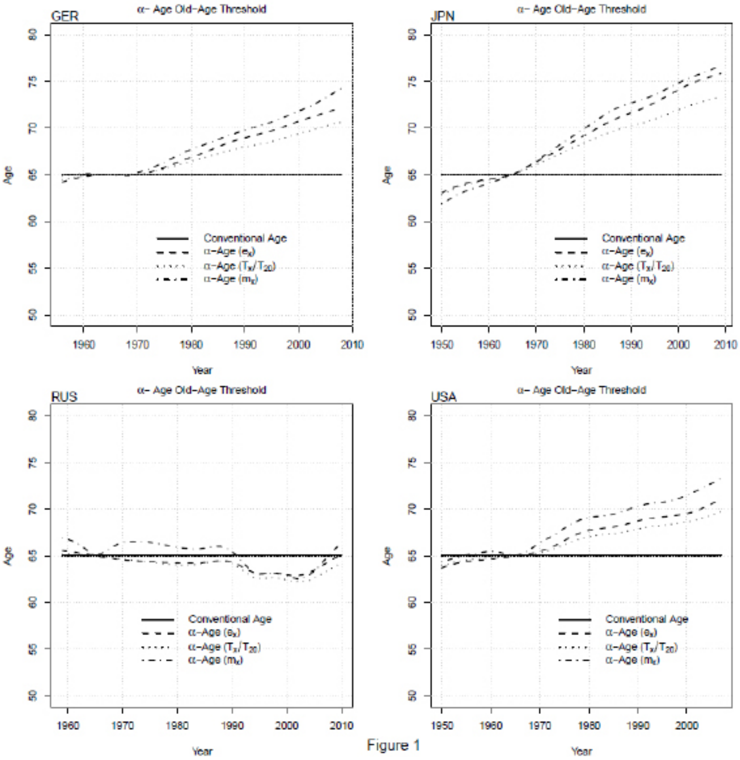

Figure 1

Figure 1. α-ages associated with three population aging characteristics - remaining life expectancy (e_x), the mortality rate (m_x), and the life-course ratio (T_x/T_{20}) – for West Germany, Japan, Russia, and the United States, c. 1950-c. 2010

Note: Spline smoothing, keeping the α-ages for 1965 equal to 65.

Source: Human Mortality Database (University of California, Berkeley & Max Planck Institute for Demographic Research 2012) and authors' calculations.

capabilities, functioning, and health of people, then changing characteristic schedules become of substantive interest. Conventional measures of population aging have the form

$$MC_t = f(S(a,t),H(a)), \tag{2}$$

where MC_t is the conventional measure of aging at time t, $S(a,t)$ is the age structure of the population at time t, and H is a matrix of age-specific characteristics. $S(a,t)$ can be a vector of the number of people by age or a matrix of the number of people by age, sex, and other informative dimensions. The key feature of conventional measures is that H is independent of time. Age structures of populations are allowed to change over time, but the characteristics of people are not. The new characteristics-based measures have the form

$$MN_t = g\big(S(a,t),H(a,t)\big), \tag{3}$$

where MN_t is the new measure and the matrix $H(a,t)$ now includes time-varying age-specific characteristics.

We discuss three families of measures. To identify them, we introduce the terms elder proportions, elder ratios, and elder relationships. *Elder proportions* have the form $\sum_a s_{a,t}h_{a,t} / \sum_a s_{a,t}$ where $s_{a,t}$ is the population at age a and time t, $h_{a,t}$ are the age-specific characteristics, and the summation is over all ages. (For example, when $h_{a,t}$ is an indicator variable that takes on the value of unity when age is 65+, we obtain the standard proportion of the population 65+ years old.) *Elder ratios* differ from elder proportions by excluding from the denominator people with the characteristic associated with the elderly. A special subset of elder ratios, α-old-age dependency ratios, *αOADR*, is based on indicator variables constructed from threshold α-ages:

$$\alpha OADR = \sum_a s_{a,t}h_{a,t} / \sum_a s_{a,t}(1 - h_{a,t}) \tag{4}$$

where the summation is from some initial age, often 15 or 20, to the maximum age. When $h_{a,t}$ is an indicator variable that takes on the value of unity when age is 65+, we obtain the standard old-age dependency ratio (OADR).

Figure 2 shows elder proportions for the four countries, where the $h_{a,t}$ are indicator variables based on the α-ages shown in Figure 1. Although the proportions 65+ rise in all countries, the most recent observations of the characteristic-based elder proportions in Germany and the US are lower than they were in 1970. Adjusting for the changing characteristics of the population allows us to see that in some ways the populations of Germany and the US have been growing functionally younger.

To illustrate elder ratios, in Figure 3 we show the conventional OADR and α-OADRs for the four countries based on the three threshold α-ages shown in Figure 1. The conventional OADR in Japan increased rapidly, but all the other α-OADRs show much more modest aging. In the US, the conventional OADR rises from 1965 onward, while the adjusted ones generally fall. The characteristics-based approach to aging provides a natural framework for seeing these differences.[3]

Elder relationships have the form $\sum_a s_{a,t}h_{a,t} / \sum_a s_{a,t}j_{a,t}$, where $h_{a,t}$ and $j_{a,t}$ refer to two different characteristics. An example of an elder relationship is provided in Figure 4. There $h_{a,t}$ and $j_{a,t}$ are indicator variables based on the α-ages in Figure 1. The $h_{a,t}$ are set to unity when age is greater than the α-age threshold associated with a remaining life expectancy of 15 years, and the $j_{a,t}$ are set to unity when age is greater than the α-age threshold associated with pension receipt (the life-course ratio, in the context of our idealized pension system). Figure 4 shows that these ratios have been decreasing over time after 1970, even for Russia. This indicates that over time fewer and fewer people receiving pensions under such a system would be considered old. Elder relationships are natural quantities to compute in the framework of a characteristic-based approach to the study of population aging, but, to our knowledge, none have previously appeared in the literature.

Elder proportions, elder ratios, and elder relationships are only three ways of incorporating changing characteristics into the study of population aging. There are clearly others - for example, as in Heigl (2002). The hallmark of the characteristics approach to the measurement of population aging is the consistent use of changing characteristic schedules

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[3] Elder ratios can use levels of the characteristics themselves rather than indicator variables. Examples include the Adult Disability Dependency Ratio (ADDR) (Sanderson & Scherbov 2010), which uses time-varying rates of severe disability, and the Cognition-Adjusted Dependency Rate (CADR) (Skirbekk et al. 2012), which uses a measure of cognition for people aged 50+.

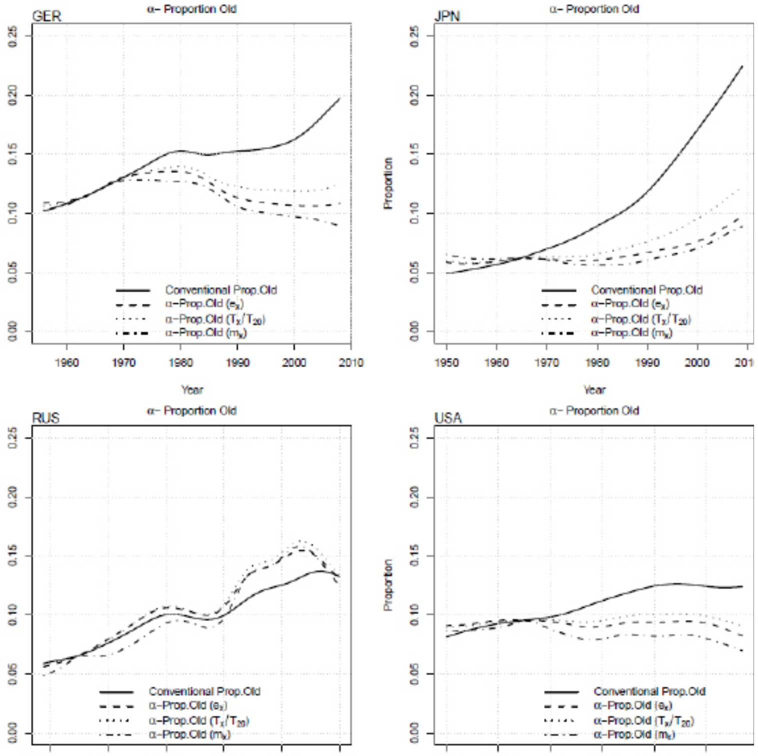

Figure 2. Elder proportions (proportions old) computed using the three α-ages in Figure 1, and fixed chronological age 65, West Germany, Japan, Russia, and the United States, c. 1950-c. 2010

Note: Spline smoothing.

Source: Human Mortality Database (University of California, Berkeley & Max Planck Institute for Demographic Research 2012) and authors' calculations.

together with changing age structures, regardless of the exact way in which the two are combined.

Implications for research and policy

Much research on population aging has been based on conventional measures. Allowing for alternative definitions of age and aging can help make the conclusions of this literature more robust. Sinn and Uebelmesser (2003), for example, argued that Germany could become a gerontocracy by 2016 because by that time there would be more voters with an incentive to vote against pension reform than there would be to vote for it. But their analysis was based on an unchanging full pension age, whereas the full pension age in Germany is already scheduled to rise from 65 to 67 and might well rise further. Our old-age threshold based on the life-course ratio is a simple way to include plausible changes in full pension ages into such analyses.

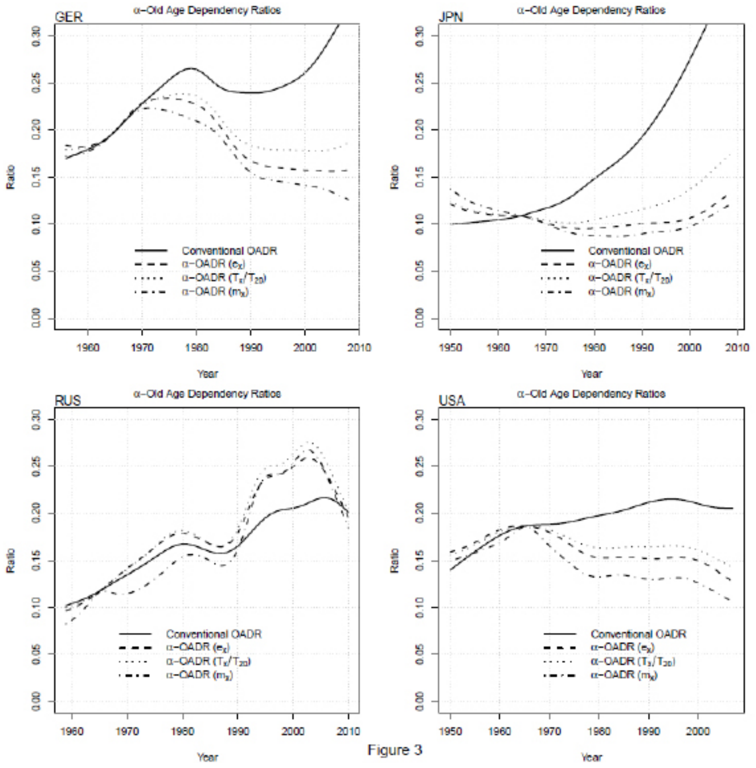

Figure 3. α-old-age dependency ratios (α-OADR) computed using the three α-ages in Figure 1, and conventional old-age dependency ratio (OADR), West Germany, Japan, Russia, and the United States, c. 1950-c. 2010

Note and Source: As for Figure 2.

Other studies that use conventional aging measures include Kelley and Schmidt (2005), exploring dependency ratio effects on economic growth, and Börsch-Supan, Heller, and Reil-Held (2011), examining the relationship between social cohesion and aging. The former finds a significant youth dependency effect but not an old-age dependency effect; the latter finds no adverse aging effect on social cohesion. Since, as we show in Figure 3, the conventional old-age dependency ratios and their α counterparts can behave quite differently, it would be worth revisiting such studies using the characteristics approach.

α-ages can also be used in place of chronological ages in investigations of health care costs. In any year, older people generally require more health care than younger ones. In many countries, health care expenditures are particularly high in the last few years of life. With life expectancy improvements, these high-cost years are deferred to older ages. Forecasts of health care expenditures that do not take into account the changing life expectancy of the population overestimate the increase in health care costs (Bjørner & Arnberg 2012; Cutler et al. 2007; Felder 2012; Martín et al. 2011). A simple approach to forecasting future health care expenditures would be to forecast them on the basis of remaining life expectancy.

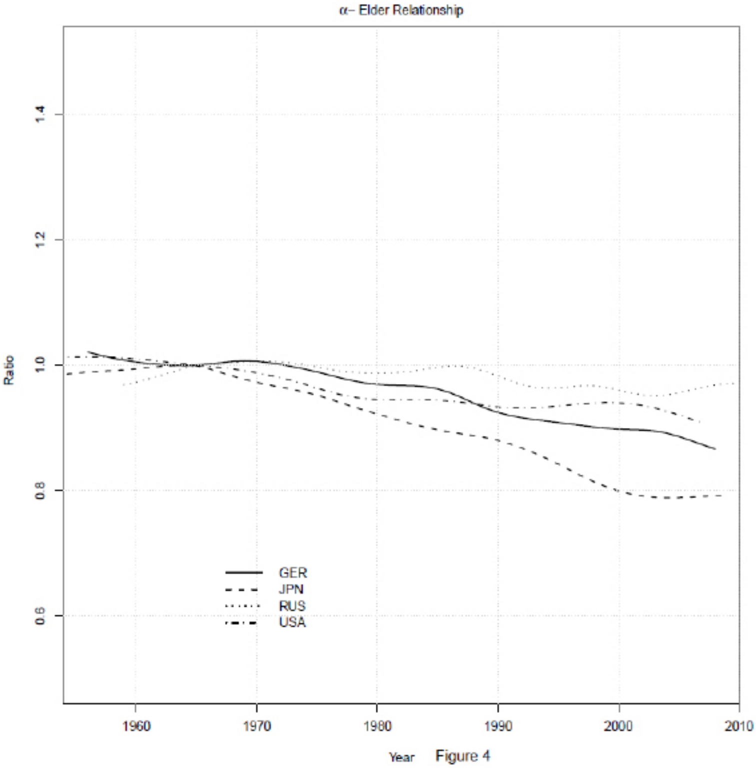

Figure 4. Elder relationships computed using the number of the population at or above the α-age associated with e_x in the numerator and the number of the population at or above the α-age associated with the life-course ratio in the denominator, West Germany, Japan, Russia, and the United States, c. 1950-c. 2010

Note and Source: As for Figure 2.

Taking the changing characteristics of people into account when studying population aging is a simple and natural way to reassess past research and introduce new perspectives on important policy questions. The approach we have discussed in this article reconceptualizes age based on the characteristics of people and allows the construction of new multidimensional measures of aging. The study of population aging based simply on chronological age, familiar for over a century, has been extremely useful for most of this period. We believe, however, that the characteristics approach set out here is more appropriate for dealing with the kinds of demographic change now underway.

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Measuring the Speed of Aging across Population Subgroups[1]

Warren C. Sanderson and Sergei Scherbov

Subgroups of populations can age at different rates. An assessment of these subgroup differences could potentially aid in improving the health of people in groups that age more quickly. Differences in the extent of aging across subgroups may also help in explaining subgroup differences in forward-looking behaviors.

The study of aging differences across subgroups necessarily involves the use of characteristics of people other than their chronological age. In estimating how much faster people in one subgroup have aged relative to another, we must specify the characteristic or characteristics that we use in this assessing this. In this article, we provide a procedure for studying differences in subgroup aging using characteristics that can be found in datasets such as CHARLS (National School of Development 2013), ELSA (The Institute for Fiscal Studies 2012), HRS (University of Michigan 2011), KLoSA (Korea Labor Institute 2013), SAGE (WHO 2013), and SHARE (Munich Center for the Economics of Aging 2013), which provide a rich array of variables that can be used to define subpopulations. We implement the procedure, in this paper, using data on a particular characteristic, hand-grip strength, but it could be implemented using many different characteristics as well.

Hand-grip strength is a measure of upper body strength that has been widely studied and that has been consistently shown to be a good predictor of future morbidity and mortality. This makes it a particularly useful characteristic in the study of differences in subgroup aging.

Bohannon (2008) reviewed 45 articles on the relationship between hand-grip strength and later mortality and morbidity outcomes. The articles included data from both healthy individuals and those with serious health conditions. Most of the studied subjects were middle-aged or older. Mortality outcomes were the subject of 24 papers. Disability was the subject of 9, and complications of surgeries or length of hospital stays was investigated in 12. A variety of other health related outcomes were also studied. Sixteen of the studies covered community-dwelling individuals, most of whom were healthy. In all the studies, low hand-grip strength was associated with greater levels of mortality, morbidity, worse health outcomes, or longer hospital stays.

Cooper et al. (2010) reviewed studies of community dwelling people that investigated the relationship between measures of physical capacity such as hand-grip strength, walking speed, standing balance, and chair rise speed with subsequent mortality. Research on hand-grip strength and mortality included studies with follow-up periods from less than 5 years to over 20. Twenty- three studies on hand-grip were analyzed using random-effects meta-analysis models and a statistically significant negative relationship between hand-grip strength and subsequent mortality was found.

Cooper et al. (2011) reviewed similar studies with subsequent fractures, cognitive decline, cardiovascular disease, and hospitalization or institutionalization as outcomes. In 9 studies of the relationship between hand-grip strength and subsequent fractures, 4 presented strong evidence that weaker hand-grip strength was associated with a greater risk of fracture, 3 presented weak evidence, and 2 showed no relationship. In 3 studies

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of the association between hand-grip strength and subsequently cognitive decline, all published strong evidence for weaker hand-grip strength being associated with future cognitive decline. In 3 studies related to cardiovascular disease, 2 studies provided strong evidence of an association, while 1 presented only weak evidence. There was 1 study of hand-grip strength and future hospitalization or institutionalization. The evidence of an association there was weak.

Ling et al. (2010) reports on a study of 555 people in Leiden, Netherlands who were 85 years old when enrolled between September, 1997 and September, 1999. Survivors were followed through February, 2008 using register data. Control variables included important comorbidities, functional status as measured by ADLs and IADLs, depression, and mental state. The main result was that study participations with relatively low hand-grip strength at age 85 had a statistically significantly higher all-cause mortality rate.

In Chen et al. (2012), 558 men 75+ years old in a nursing home in Taiwan were followed for 3 years. Low hand-grip strength was statistically significantly associated with the risk of infection-related death.

Rantanen et al. (2012) reported on a study of 2,239 men who were born before June, 1909 and had hand-grip strength measurements taken between 1965 and 1968 when they were between 56 and 68 years old. The observation period ended in June, 2009 when all the men had either died or reached the age of 100+ years old. When centenarians were compared with those who died at age 79 or earlier, it was found that they were 2.5 times (95% confidence interval (1.23–5.10)) more likely to have had hand-grip strength in the top third on the baseline hand-grip strength distribution. This study also had an observation not found in any of the previous research. Multivariate analysis suggested that mother's longevity and her offspring's hand-grip measured at mid-life affected the offspring's longevity through similar path- ways. The causes of this association are unclear. It could be that there is a genetic component to hand-grip strength. Another possibility is that mothers with higher education had higher life expectancies themselves and raised healthier children who subsequently had stronger hand-grips. Evidence consistent with the hypothesis of a connection between parental longevity and hand-grip strength can also be found in Frederiksen et al. (2002).

Ortega et al. (2012) analyzed data from 1,142,599 Swedish adolescent males born between 1951 and 1976, based on the Swedish Military Conscription Register. At that time all Swedish young men had to take pre-conscription examinations even if they did not subsequently serve in the armed forces. Only young men with severe handicaps or chronic diseases were exempt from those tests. The young men were followed until the earliest of three outcomes, death, emigration or the end of data collection on December 31, 2006. The median follow-up period was 24.2 years, with a range of 1.0 to 37.3 years. Data were unused if the follow- up period was less than a year (to eliminate those who were very sick when the exams were given), or if the subjects had extreme readings on their height, weight, body mass index, or on their blood pressure. Four outcomes were delineated, all-cause mortality, mortality from cardiovascular disease, cancer and suicide. Using Cox proportional hazard models, the authors showed that lower hand-grip strength, particularly for those with hand-grip strengths below the median, were significantly associated with higher all-cause mortality, higher mortality from cardiovascular disease, and a higher risk of suicide. Hand-grip strength was not associated with the risk of dying of cancer. In an exploratory supplementary analysis, the authors found that low hand-grip strength among the adolescents was also predictive of the development of subsequent psychological problems.

As the studies above show, low hand-grip strength has been shown definitively to predict poor outcomes in a wide variety of mortality, morbidity, and other health outcomes such as lengths of stay in hospitals or rehabilitation centers. The associations have been demonstrated for both younger and older people, for community-dwelling populations and those in institutions, and for people in many different countries. Because of these associations with a wide variety of characteristics that are associated with aging, hand-grip strength is a useful metric for assessing how fast sub-groups of a population have aged.

Methods

The data that we use here are from the 2006, 2008, 2010, and 2012 waves of the Health and Retirement Survey (HRS) (University of Michigan 2013). The HRS is sponsored by the National Institute on Aging (grant number NIA U01AG009740) and is conducted by the University of Michigan. Hand-grip strength was initially collected in a small sample of the HRS participants in 2004, but the later four waves are more comparable in survey design and implementation. Table S1 shows mean hand-grip strength by 5 year age groups from 60– 64 to 80–84 cross-classified by race, gender, and education. Hand- grip strengths were measured in kilograms using a Smedley spring- type dynamometer and are derived as the average of four observations, two for each hand. We investigate the effect of education on hand-grip strength with random-effects panel regressions using the specification:

$$hg_{i,j} = \beta_0 + \beta_1 age^2_{i,j} + \beta_2 age^2_{i,j} LowEd_i + \beta_3 LowEd_i + \beta_4 Height_{i,j} + \beta_5 Weight_{i,j} + \beta_6 Wave2008 + \beta_7 Wave2010 + \beta_8 Wave2012 + \mu_i + \varepsilon_{i,j}$$

or more compactly $hg_{i,j} = X_{i,j}\beta + \mu_i + \varepsilon_{i,j}$.

The dependent variable is the hand-grip strength of person *i* in wave *j*. The independent variables are age^2, a dummy variable indicating that formal education was completed prior to obtaining a high school degree (*LowEd*), the interaction of age^2 and *LowEd*, height, weight and dummy variables indicating the HRS wave.

The person-specific component, μ_i, is assumed to be a normally distributed IID random variable which is uncorrelated with the independent variables and with the idiosyncratic random term, $\varepsilon_{i,j}$. All regressions are run separately for white men, white women, African-American men, and African-American women on data from which extreme outliers were removed. Details about this eliminated cases can be found in Text S1. Information about the independent variables that we used can be found in Table S2. In each of these four groups there are two disjoint panels, one for the years 2006 and 2010 and another for the years 2008 and 2012. We tested specifications linear in age and found that the inclusion of age linearly did not increase the adjusted R^2 and made the other coefficient estimates less precise. The results of the regressions can be found in Text S2.

Our prefered specification has no correction for selectivity and does not use weights. We did tests for selectivity using the Heckman 2-step procedure and found none (see Text S3). Weights appropriate for hand-grips strength measures are currently available only for 2006 and 2008. Therefore it was impossible to use weights in the panel estimates. We did tests for the sensitivity of our results to the use of weights using the 2006 and 2008 data separately and found that our results regarding age differentials were robust to whether or not weights were used (see Tables S3 and S4).

The predicted mean hand-grip stregth conditional on a set of covariates X^* is

$$E(hg|X^*) = X^*\hat{\beta},$$

where $E(.)$ is the expectation operator and $\hat{\beta}$ is a vector of estimated regression coefficients. Our interest is in the chronological ages of subpopulations with equivalent mean hand-grip strengths. Holding height, weight, and wave constant and denoting the chronological age of people with low education age_L, for a given set of estimated coefficients, $\hat{\beta}$, the age of more educated people with the same mean hand-grip strength can be computed as

$$\widehat{age}_H = \sqrt{age_L^2 + \frac{\hat{\beta}_2}{\hat{\beta}_1} age_L^2 LowEd + \frac{\hat{\beta}_3}{\hat{\beta}_1} LowEd}$$

The estimated parameter vector $\hat{\beta}$ is itself random and therefore $\widehat{age}_H$ is random, conditional on values of age_L^2 and *LowEd*. Given the variance-covariance matrix of $\hat{\beta}$, we simulated 1,000 values of $\hat{\beta}_i$ $(i = 1,2,3)$ and the corresponding distributions of $\widehat{age}_H$. These $\widehat{age}_H$ are constant characteristic ages, as defined in Sanderson and Scherbov (2013).

Findings

The means and the 95% confidence intervals for $\widehat{age}_H$ are shown in Table 1 for the four race-gender groups.

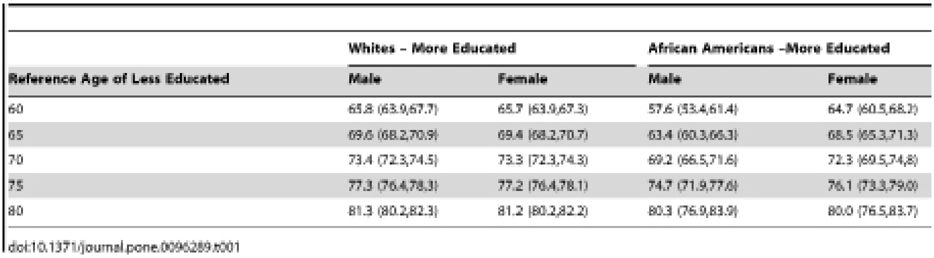
We can see from Table 1 that white males and females and African-American females with a high school education or more age less rapidly than those with less than a high school education. The advantage associated with more education diminishes as people get older and essentially disappears by age 80. African- American males differ in that no statistically significant differences by education in hand-grip based ages can be found.

Discussion

Table 1 shows converge in two dimensions. First, educational differentials in hand-grip based ages tend to disappear as people get older. Second, racial differences also disappear as populations age. Selectivity by frailty and perhaps other characteristics likely accounts for a portion of this convergence. There could also be cohort differences in the effects of education. Eighty year olds were educated at an earlier time than 60 year olds and the contents of their educational experiences with respect to health could have been different. The lack of an effect of education for African- American men, while there is one for African-American women in their 60’s needs further study. Roughly speaking, the African- American men and women grew up in similar early health environments and had comparatively similar early educational experiences. Possibly, African-American women with a high school education or more worked in occupations with greater access to health-relevant information or better health insurance compared to African-American men with a similar level of education.

A number of papers have produced biomarker-based biological ages. These have been oriented to studying the ageing process in individuals and not to measuring subgroup differences in health. There is no consensus on the best approach to determining biological age. Levine (2013) evaluates a number of these and found that a variant of the Klemera and Doubal (2006) method predicts future mortality best. However, the Klemera and Doubal procedure is complex and requires ad hoc assumptions. In contrast, the approach put forward here is simple and transparent.

Table 1. People with the same hand-grip strength based age, by age, gender, race, and education, means and 95% confidence intervals.



	Whites – More Educated		African Americans –More Educated	
Reference Age of Less Educated	Male	Female	Male	Female
60	65.8 (63.9,67.7)	65.7 (63.9,67.3)	57.6 (53.4,61.4)	64.7 (60.5,68.2)
65	69.6 (68.2,70.9)	69.4 (68.2,70.7)	63.4 (60.3,66.3)	68.5 (65.3,71.3)
70	73.4 (72.3,74.5)	73.3 (72.3,74.3)	69.2 (66.5,71.6)	72.3 (69.5,74.8)
75	77.3 (76.4,78.3)	77.2 (76.4,78.1)	74.7 (71.9,77.6)	76.1 (73.3,79.0)
80	81.3 (80.2,82.3)	81.2 (80.2,82.2)	80.3 (76.9,83.9)	80.0 (76.5,83.7)

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In this paper, we have presented a simple procedure for using a biomarker, hand-grip strength, to produce a comparative measure of aging across population subgroups. Because our measure is a characteristic-based age (see Sanderson & Scherbov 2013) it is easy to understand, interpret, and communicate to policy-makers.

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Are We Overly Dependent on Conventional Dependency Ratios?[1]

Warren C. Sanderson and Sergei Scherbov

This year is the 102nd anniversary of the introduction of the dependency ratio, or more precisely, its inverse (Ballod 1913). The dependency ratio, and its components, the youth dependency ratio and the old age dependency ratio have had a long and productive life, but it is time to consider their retirement. Today, there are alternatives that do their jobs better.

The ratios that we discuss in this paper are all ratios of weighted age-specific populations. When both genders are combined, the form of these ratios is:

$$R_{i,t} = \frac{\sum_{a=0}^{\omega} v_{a,i,t} \cdot P_{a,i,t}}{\sum_{a=0}^{\omega} w_{a,i,t} \cdot P_{a,i,t}} \qquad (1)$$

where *a* is chronological age, *i* is an indicator of a particular place, *t* refers to a specific time period, $v_{a,i,t}$ and $w_{a,i,t}$ are two different sets of age-, place-, and time-specific weights, $v_{a,i,t} = 0$ is the population of age *a* in place *i* at time *t*, *ω* is the highest possible age, and $v_{a,i,t} = 0$ is a dependency or support ratio.

To avoid confusion, we call ratios which have the producers in the denominator and those that they support in the numerator dependency ratios. We call ratios which reverse these and put the producers in the numerator and those that they support in the denominator support ratios. Arguments related to one of them apply to the other, suitably adjusted.

The United Nations produces five dependency ratios and five old age dependency ratios. The period of youth dependency is defined as ranging from birth through ages 14, 19, or 24. The period of old age dependency is defined as ranging upward from either age 65 or 70. The combination that is not computed is the case of young dependency ending at age 14 and old age dependency starting at 70 (United Nations 2015). It is cumbersome to deal with all those dependency ratios. For clarity, we will focus here on the dependency ratios, where youth dependency ends at age 19 and old age dependency begins at age 65. The most important feature of the traditional dependency ratios, from our perspective, is that they are conceptualized and computed using fixed chronological ages that are independent of time, place, and the nature of dependency. Exactly which fixed chronological ages are used, 14, 19, or 24 for the end of youth dependency and 65 or 70 for the beginning of old age dependency are less important.

To make the argument that there exist preferable alternatives to the dependency ratio and the old age dependency ratio for measuring important dimensions of population aging, we structure our discussion in two steps. First, we specify an objective for which the ratios have been used. Second, we show that either currently existing or easily computed alternative measures meet that objective better.

In the first section below, we provide a brief history of dependency ratios and support ratios including the economic support ratio used in the National Transfer Accounts (NTA)

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research program (Lee & Mason 2011). To our knowledge, the support ratio first appeared in 1913 (Ballod 1913) and the NTA economic support ratio in 1931 (Günther 1931). Ballod's motivation was to quantify the ratio of people who were not in the labor force to those who were. In Section 3, we discuss this objective and note that the ILO has provided estimates and forecasts of age-, country-, and time-specific labor force participation rates. Using these and UN population age structures, the compute the ratio of people not in the labor force to those who are and show that the dependency ratio is often a poor approximation to that ratio.

We discuss the NTA economic support ratio in the third section. This ratio has in the numerator the number of standardized producers (based on labor income) and the number of standardized consumers (based on levels of consumption) in the denominator. Günther (1931) used this ratio to discuss the relationship between demographic change and economic stagnation in Germany. Currently, this ratio is also used in discussions of economic growth. In this section, we show that the dependency ratio is often a poor approximation to the inverse of the NTA economic support ratio. In this section, we also discuss a new definition of financial dependency based on who is receiving and who is providing net transfers to others.

Perhaps the old age dependency ratio could be used as an approximation to the effects of population aging on healthcare costs. We investigate this in Section 5. Healthcare costs are especially high in the last few years of life (Fuchs 1984; Lubitz et al. 2003; Riley & Lubitz 2010). This is a time when a high fraction of all the healthcare costs for the elderly are incurred. To test whether the old age dependency ratio is a useful approximation to the effects of aging on healthcare costs, we compute *healthcare cost old age dependency ratios*. For comparison, we use ratios of the number of people 50 years old and above who will die in the subsequent five year period to the adult population. We show that the old age dependency ratio is often a poor approximation to these ratios. The exact parameters of this ratio are illustrative, but the results would be the same if we had used age 65 instead of 50 and a period starting three years before death instead of five or any other set of plausible parameters.

Perhaps the old age dependency ratio could be used as an approximation to the effects of population aging on pension costs. In most OECD countries, normal pension ages and pension eligibility rules are in the process of changing (OECD 2014; OECD 2013). Some OECD countries have introduced explicit demographic indexation of their pensions. In Section 6, we use a newly developed intergenerationally equitable pension age (Sanderson & Scherbov 2015) which varies with survival rates to produce a *pension cost dependency ratio*. This ratio is the number of people at or above the intergenerationally equitable pension age to people between the ages of 20 and that pension age. We show how the pension cost dependency ratio changes over time for OECD countries. We demonstrate that the old age dependency ratio is often a poor approximation to this ratio. The age 20 here is used to obtain a series which can be used for comparison. The same poor approximation would be observed if we had used any plausible starting age.

The discussion in the previous sections deals with the old age dependency ratio in terms of labor market participation, provision and receipt of net transfers, health care costs, and pension entitlements. What is missing up to this point is a discussion of the relationship between the old age dependency ratio and who is old. In Section 7, we discuss a version of the old age dependency ratio based on a flexible definition of who is old. We do not assume that people become old on their 65th birthdays regardless time, place, and other characteristics. Instead, we stipulate that people become old when they get near the end of their lives. We call the ratio using this definition of who is old the *prospective old-age dependency ratio* (Sanderson & Scherbov 2013; Sanderson & Scherbov 2010; Sanderson & Scherbov 2007; Sanderson & Scherbov 2005). The prospective dependency ratio is a general measure of population aging that takes changes in life expectancy into account. In Section 7, we show that the old age dependency ratio is also often a poor approximation to the prospective old age dependency ratio.

A brief history of dependency and NTA support ratios

The forerunner of the dependency ratio first occurs in a book written in German by Karl Ballod, the title of which can be translated as "Statistical outlines, including demographic, economic, financial, and commercial statistics" (Ballod 1913). Ballod called his ratios *Belastungskoeffizienten*, or coefficients of burden. Ballod's coefficient of burden was more precise than today's dependency ratio. He divided populations into five age groups, children aged 0-14, teenagers aged 15-20, adults fully capable of working aged 21-59, elderly with reduced capacity for work aged 60-70, and the very old aged 71 and older, who are assumed to be incapable of working. Teenagers and older people with reduced capacity for work were assumed to be able to support only themselves. Thus, the coefficient of burden was defined as the ratio of children and the very old to prime-age adults.

Ballod's coefficient of burden, then, can by written simply as a specific case of equation (1) where $v_{a,i,t} = 0$ for *a* in the range 21 to 59, $v_{a,i,t} = 0$ outside of this age range, $w_{a,i,t} = 0$ for age 0 through 14 and 71 and older, and $w_{a,i,t} = 0$ for all other ages. Tabulations of populations by age groups was common well before 1913. Ballod's addition was his conceptualization that some groups of people are burdens to others.

In his 1913 book, Ballod provides statistical snapshots of countries and regions, one of which describes how Germany, Austria, France, Italy, and the US differ in their coefficients of burden.

Ballod's work on the dependency ratio was recognized as important and innovative in the Russian-language literature (Tkachenko 2013), probably because he was a Marxist. Possibly for the same reason, it was ignored in the demographic literature in German and English. It is unclear whether Ballod's formulation had any effect on the subsequent development of the dependency ratio in English. In any case, it is likely that the dependency ratio and the support ratio were independently reinvented in the English-language literature.

In the 1930s, the leading figures in making cohort-component population projections were Warren S. Thompson and P. K. Whelpton. In 1933, they published a path-breaking volume that used scenario-based cohort- component population projections in much the way they are still used today (Thompson & Whelpton 1933). They produced forecasts of the population sizes of age groups, but did not compute a dependency ratio. Instead, they calculated an expanded version of what is now called the NTA economic sup- port ratio following Günther (1931). As they summarized, "an attempt has been made to measure the probable changes in the productive power of the population in relation to its consumption needs by assigning weights for both factors by age and sex" (Thompson and Whelpton 1933, p. 168).

The weights used are shown in Table 1. The production weights correspond to the *v* coefficients in equation (1) and the consumption weights to the *w* coefficients. Thompson and Whelpton cite Günther (1931) as the source of the ratio that weights people by their incomes in the numerator and by their consumption in the denominator. The weights in

Table 1. Weights used in the calculation of the economic support ratio for the United States

	Production Weights (v_a)		Consumption Weights (w_a)	
Age Group	**Male**	**Female**	**Male**	**Female**
0-4	0.00	0.00	0.30	0.30
5-9	0.00	0.00	0.40	0.40
10-14	0.00	0.00	0.60	0.60
15-19	0.50	0.25	0.85	0.75
20-24	1.00	0.50	1.00	0.80
25-29	1.00	0.50	1.00	0.80
30-34	1.00	0.50	1.00	0.80
35-44	1.00	0.50	0.95	0.80
45-54	0.80	0.40	0.90	0.75
55-64	0.60	0.30	0.85	0.70
65-74	0.40	0.20	0.70	0.65
75+	0.10	0.00	0.70	0.65

Note: Günther's (1931) economic support ratio has the same form as the current NTA support ratio, except that the two sexes are distinguished in the former.

Source: Thompson and Whelpton (1933, Table 45, p. 169).

Table 1 come in part from Günther (1931) with modifications to the income weights based on Sydenstricker and King (1921). The productivity weight for men 65-74 in Table 1 is 0.4, far from the value of zero assumed in the dependency ratio.

The work of Günther and of Thompson and Whelpton was independently reproduced by Cutler et al. (1990), which led to its subsequent use in the National Transfer Accounts project. Both Günther (1931) and Cutler et al. (1990) were motivated by their interest in the macroeconomic effects of demographic change. In one respect, Günther and Thompson and Whelpton were more precise than Cutler et al. (1990) and the current NTA economic support ratios because the earlier studies explicitly included both sexes. Re- search is underway to include calculations related to both sexes more explicitly in the NTA framework.

The first use of the term "total dependency ratio" and its first analysis in the form that is common today was in Notestein et al. (1944, Chapter 7, pp. 153-163). The total dependency ratio is defined there as the ratio of people 0–14 years old and those 65+ years old to those 15–64. Although the youth dependency ratio and the old-age dependency ratio are computed and presented in graphs, the terms "youth dependency ratio" and "old-age dependency ratio" did not appear there. That terminology emerged even later. Notestein et al. (1944) are clear about their interpretation of the age boundaries. They write, "Any age limits set for the productive and dependent groups are bound to be inadequate for the heterogeneous area [Europe and the Soviet Union] and the thirty-year period under consideration. Nevertheless, uniformity of treatment requires that some arbitrary limits be set" (p. 153). Despite this caveat, those age boundaries are currently being used for all countries of the world and for the time span 1950 to 2100.

Notestein et al. also provide an economic motivation for studying the dependency ratio. They distinguish three stages of dependency associated with progression through the demographic transition: "(1) heavy youth dependency, (2) light dependency, and (3) heavy old-age dependency.” They continue: “The economic advantage of this second stage of light dependency is enhanced by the fact that growth is ending at the same time, thereby releasing society from the need of expanding its durable goods merely to accommodate increasing numbers. Apart from problems of the dynamics of the economy and those of the efficient use of older workers, the demographic position favors high productivity per capita” (p. 155). This approach is familiar today in the study of the demographic dividend, where demographic change is also used in the analysis of economic growth.

Shortly after Notestein et al. (1944) was published, Frank Notestein became the first director of the United Nations Population Division. Subsequently his version of the dependency ratio became a standard measure of aging used by the UN. The dependency ratio and its offshoot, the old-age dependency ratio, are now among the most frequently cited statistics in the discussion of aging. Since the early days of the dependency ratio, far more data have become available and new approaches to the study of population aging have been developed. In what follows, we assess whether the dependency ratio is still the best way of measuring various aspects of population aging or whether new data and new methods have rendered it primarily of historical interest.

Economic dependency ratios

The original uses of the dependency ratio were as approximations to the ratios of non-workers to workers. In the years when the ratio was first used for this purpose, it was the best approximation available that could be consistently measured both across countries and over time. This, however, is no longer the case. The ILO has produced consistent series of labor force participation rates for all UN countries with forecasts to 2030 (ILO 2011). Applying these participation rates to UN population forecasts produces consistent forecasts for the ratio of non-workers to workers, called the economic dependency ratio (EDR). In equation (1) the v_a coefficients are $lfpr_a$ and the w_a coefficients are $lfpr_a$ where $lfpr_a$ is the labor force participation rate for people of age *a* (both sexes combined).

In Table 2, we show the percent change in the economic dependency ratio and the (total) dependency ratio between 2013 and 2030 for OECD countries. We use OECD countries in our tables because data are of high and consistent quality. This is especially important in Table 2 because the ILO labor force participation projections are based on labor market surveys.

Approximating the economic dependency ratio has been one of the main uses of the dependency ratio. In Table 2, we show the accuracy of this approximation by comparing the percent increases in the two ratios between 2013 and 2030, when the ILO labor force participation rate forecasts end. In almost all countries, the direction of change in the two ratios is the same. In a few – for example Chile, where the economic dependency ratio decreases by 7.1 percent and the dependency ratio increases by 11.8 percent – the directions of change differ. The magnitudes of the changes, though, are often quite different. In the UK, for example, the economic dependency ratio increases by 1.0 percent while the dependency ratio increases by 16.5 percent. In South Korea the increase in the economic dependency ratio is 1.2 percent while the increase in the dependency ratio is 38.6 percent. The figures in the table tell a clear story. Changes in the dependency ratio are not a good approximation to changes in the economic dependency ratio. When there were no labor force participation rate projections for most countries of the world produced with a consistent methodology, we might have used changes in the dependency ratio

Table 2. Percent change in the economic dependency ratio and total dependency ratio from 2013 to 2030, OECD countries

Country	Economic Dependency Ratio (EDR)	Total Dependency Ratio (TDR)
Australia	3.6	20.9
Austria	8.4	26.1
Belgium	4.3	24.8
Canada	14.1	36.4
Chile	-7.1	11.8
Czech Rep.	3.6	26.2
Denmark	-3.4	14.4
Estonia	1.4	18.3
Finland	8.8	27.3
France	6.2	19.4
Germany	11.1	30.6
Greece	3.4	18.7
Hungary	-1	14.5
Iceland	3	17.2
Ireland	-2.5	13.1
Israel	4.7	2.2
Italy	-1	22.3
Japan	-1.8	19.7
Korea, Republic of	1.2	38.6
Luxembourg	6.4	16.9
Mexico	-19.2	-15.6
Netherland	11.5	26.4
New Zealand	4.7	17.4
Norway	3.1	16.1
Poland	7.4	37.4
Portugal	-2.9	14
Slovakia	10.6	31.7
Slovenia	12.7	36
Spain	3.5	22.2
Sweden	10.8	17.7
Switzerland	12.6	20.9
Turkey	-8.3	-7.8
UK	1	16.5
USA	2.9	22.3

Note: The youngest people in the numerator of the ratios are 20 years old.

Source: Authors' calculations based on data from United Nations (2013) and ILO (2011).

as a proxy for changes in the economic dependency ratio. Now, however, it is no longer necessary to do so.

What if forecasts of the economic dependency ratio were needed beyond 2030? Clearly, given the differences between the two rates, using the dependency ratio as an approximation to the economic dependency ratio could be problematic. One approach to making forecasts beyond 2030 would be to hold age-specific labor force participation rates fixed at their 2030 levels. Another approach would be to let the labor force participation rates move to the level of a similar country in 2030. Either of these approaches is likely to produce more realistic projections than would be obtained by using an approximation based on the dependency ratio.

Further research will certainly be done on methods for forecasting labor force participation rates. Population forecasts are now available by age, sex, and educational attainment for most countries of the world (Lutz et al. 2014), and these might be integrated into future labor force participation forecasts. Nevertheless, if people are interested in the evolution of the ratio of those out of the labor force to those who are in the labor force, there is no reason to ignore economic dependency ratios that use the ILO labor force participation forecasts. At present, these are the best consistently produced forecasts available for most countries of the world.

NTA economic support ratios

The National Transfer Accounts (NTA) research project (Lee & Mason 2011; National Transfer Accounts Project n.d.) has compiled a wealth of information on generational accounts. The dependency ratio was created to provide information on the amount of resources that each working person on aver- age had to transfer to each non-working person – essentially, to those in the older and younger generations. With the NTA data, it is no longer necessary to approximate these intergenerational flows. They are now available in detail. One output of the NTA project has been NTA economic support ratios. In general terms, the NTA economic support ratio is the ratio of the effective number of workers to the effective number of consumers.

More precisely, let $y_{a,i,t}$ be the average per capita income of people of age a, in place i, at time t and let $c_{a,i,t}$ be the average per capita consumption of people of age a, in place i, at time t. Then the NTA economic support ratio can be computed from equation (1) with

$v_{a,i,t} = \frac{y_{a,i,t}}{\bar{y}_{30-49,i,t}}$, where $\bar{y}_{30-49,i,t}$ is the average labor income of 30-49 year-olds in place i in year t. Similarly, $w_{a,i,t} = \frac{c_{a,i,t}}{\bar{c}_{30-49,i,t}}$,

where $\bar{c}_{30-49,i,t}$ is the average consumption of 30-49 year olds in place i in year t. (National Transfer Accounts Project n.d.)

An important advantage of the NTA research project is the detail and care with which the generational transfer accounts have been constructed. The downside of this is that fully detailed generational transfer accounts have been produced for only a few years.

The Interactive Data Explorer on the NTA website (National Transfer Accounts Project n.d.) permits the calculation of NTA economic support ratios for 40 countries for the period 1950 to 2100 using UN medium-variant population projections and the weights for a standard year, s. Those NTA support ratios then have the form

$$R_{i,t} = \frac{\sum_{a=0}^{\omega} v_{a,i,s} \cdot P_{a,i,t}}{\sum_{a=0}^{\omega} w_{a,i,s} \cdot P_{a,i,t}}$$

Table 3 shows the percent change in the dependency ratio and the inverse of the NTA economic support ratio from 2013 to 2030 and from 2013 to 2050 for OECD countries for which data were given in the NTA Interactive Data Explorer. Both are based on the 2012 revision of UN population data. Clearly, increases in the dependency ratio are not a good proxy for increases in the inverse of the NTA support ratio. For example, the dependency ratio in Hungary increases by 41.4 percent from 2013 to 2050, while the inverse of the NTA support ratio increases by 16.2 percent. Canada's dependency ratio increases by 45.0 percent from 2013 to 2050, while the inverse of the NTA support ratio increases by 17.4 percent. NTA data are continually being extended and improved. Recent developments include the incorporation of time allocation and the profiles of consumption and production separately by sex (Hammer et al. 2015; Loichinger et al. 2014).

NTA data provide the ability to quantify financial dependency in detail. One concept of financial dependency is based on employment status. A person could be considered financially dependent if he or she is not in the labor market, but this is a very narrow definition of financial dependency. Some people are not working because they have accumulated enough wealth to live off their capital income. Using current NTA data, our

Table 3. Percent change in the total dependency ratio and inverse of the NTA support ratio from 2013 to 2030 or 2050, selected OECD countries

	Total Dependency Ratio		**Inverse NTA Support Ratio**	
Country	**2030**	**2050**	**2030**	**2050**
Australia	15.8	28.1	8.2	12.9
Austria	12.1	45.3	14.1	21.9
Canada	24.5	45.0	11.0	17.4
Chile	4.0	29.2	4.1	13.4
Finland	21.8	27.7	11.3	12.9
France	13.6	27.1	10.8	13.9
Germany	14.6	53.3	19.1	30.6
Hungary	15.4	41.4	3.6	16.2
Italy	12.1	60.0	13.4	26.7
Japan	15.8	52.9	10.4	27.6
Korea, Republic of	17.3	104.4	13.3	34.3
Mexico	-13.5	-6.5	12.5	15.2
Slovenia	28.2	72.3	18.2	31.9
Spain	15.0	85.5	15.0	37.3
Sweden	14.2	20.1	8.4	12.5
Turkey	-7.6	7.7	-3.5	0.0
UK	10.9	26.4	10.0	14.9
USA	15.6	24.7	9.7	12.9

Note: Total dependency ratio is computed assuming youth dependency continues through age 19. Data are for OECD countries that have data in the NTA Interactive Data Explorer as of July 2015 (National Transfer Accounts Project n.d.). The NTA Interactive Data Explorer also contains data for non–OECD countries. Dates of the standard labor income and consumption schedules do not appear in the NTA Interactive Data Explorer.

Source: Authors' calculations based on data from National Transfer Accounts Project (n.d.)

preferred measure of financial dependency is based on the net value of all transfers to and from people. The receipt or provision of net transfers provides a more complete picture of financial dependency than we have had up to this point. It takes into account, for example, whether people are working in the labor market, whether they are receiving a pension, and the portion of the value of health care services that they consume that is paid for by others. If nursing home care is financed by others, it is also counted as a transfer to the person. Often people make and receive transfers at the same age. For example, if a retired person purchases an item and pays value-added or sales tax on it, that per- son would be providing a transfer to others through the payment of those taxes and might at the same time be receiving transfers from others through a pension or the coverage of health care expenditures. Because people can simultaneously be receivers and providers of transfers, we define financial dependency on the basis of net transfers.

Transfers to young children are initially positive, but eventually as those children mature they provide net transfers to others. We call the age at which the direction of net transfer receipts changes from positive to negative the *younger transfer transition age* (YTTA). As adults grow older, their transfers to others diminish and eventually they again receive net transfers from others. We call the age at which transfers change from negative to positive the *older transfer transition age* (OTTA).

The period from birth to the YTTA is a clearly defined measure of the period of youth financial dependency. The period from the OTTA to death is a clearly defined measure of the period of old-age financial dependency. We show in Table 4 the transfer transition ages for all countries with available data. Whereas in the conventional dependency ratio the YTTA is assumed to be 15 and the OTTA is assumed to be 65, Table 4 demonstrates that in fact there is a wide variety of transfer transition ages. In the UN's dependency ratio, the age at which people stop becoming dependents is 15. In other calculations it is sometimes 20. In Table 4, we see that net transfers often continue to be made to children through their mid-20s. As more NTA data become available, we will be able to see how the ages at which people become net providers of transfers to others change. The current generation of NTA data, however, suggests that the assumption that everyone between ages 15 and 64 is a net provider of transfers to others is far from being the case.

In Table 3 we showed time profiles of inverse NTA support ratios based on schedules of labor income and consumption fixed at the latest year for which data were available. Of course, we would expect those schedules to change over time. In most OECD countries, pension reforms and increases in the labor force participation rates of older people suggest that transfers to older people, at each age, are likely to diminish over time. Taking this into account would result in inverse NTA support ratios rising less rapidly than shown in Table 3. This is not, however, what we would expect to see generally. In Table 4, the OTTA for Indonesia in 2005 was 81.4 years. Since that time Indonesia has had a pension reform that will lead to greater transfers to the elderly. In countries like Indonesia where national pension systems are expanding their coverage, it is likely that OTTAs will fall and transfers to the elderly will increase. As a result, inverse NTA support ratios in those countries could rise more rapidly than shown in Table 3.

Health care cost old-age dependency ratios

Health care costs are especially high in the last few years of life, and a substantial fraction of all health care expenditures on the elderly are made during these years (Fuchs 1984; Hogan et al. 2001; Lubitz et al. 2003; Miller 2001; Riley & Lubitz 2010). As life expectancy increases, these last few years of life occur later and later. The literature

Table 4. Age ranges of financial dependency: younger transfer transition age and older transfer transition age, NTA countries

Country/Region	Year	Younger Transfer Transition Age (YTTA)	Older Transfer Transition Age (OTTA)
Austria	2000	20.3	57.5
Brazil	1996	24.7	61.7
Costa Rica	2004	24.2	61.9
Finland	2004	21.2	59.1
Germany	2003	25.5	61.0
Hungary	2005	23.2	57.4
India	2004	24.9	70.4
Indonesia	2005	27.6	81.4
Japan	2004	24.5	62.2
Korea, Republic of	2000	26.5	62.8
Mexico	2004	25.6	70.5
Philippines	1999	25.3	70.6
Slovenia	2004	24.2	56.2
Spain	2000	25.8	60.3
Sweden	2003	23.1	63.6
Taiwan	1998	23.7	57.1
Thailand	2004	25.4	62.1
USA	2003	24.8	64.1

Note: All countries for which data were publicly available on net transfers as of July 2015. These data do not come from the NTA Interactive Data Explorer, but from detailed tables elsewhere on the NTA website. Net transfers are made to people below the YTTA and above the OTTA. People between those ages provide net transfers to those who are older and younger.

Source: National Transfer Accounts Project (n.d.).

suggests that the old-age dependency ratio, which does not take changes in life expectancy into account, is unlikely to be an accurate predictor of health care costs. Here we show that there is an easily available alternative measure that could possibly do the job better.

To compute health care cost old-age dependency ratios, we make some assumptions about who is defined as elderly and when the period of rapidly increasing health care costs begins. As an example, we consider the deaths of all people aged 50 years and older and assume that the period of rapidly increasing health care costs begins at five years before death. The dynamics of the health care cost old-age dependency ratio would be similar for any plausible starting age other than age 50 and for any plausible period before death. In Table 5, we compare increases in health care cost old-age dependency ratios and old-age dependency ratios. In a few cases, the percent changes are similar. For example, the health care cost old-age dependency ratio in the Netherlands increases by 76 percent from 2013 to 2050, while the old-age dependency ratio increases by 85 percent. In most cases, the discrepancies are much larger. An extreme example is Turkey, where the health care cost old-age dependency ratio increases by 34 percent from 2013 to 2050 and the old-age dependency ratio increases by 196 percent.

It is a simplification to compute health care cost dependency ratios for the last few years of people's lives. Other factors also matter. Nevertheless, the fact remains that a great deal of the health care expenditures on the elderly occur in the last few years of their lives. The health care cost old-age dependency ratio presented here takes into account this quantitatively important feature of health care spending that is ignored in the old-age dependency ratio.

Table 5. Percent change in the health care cost old-age dependency ratio and the old-age dependency ratio from 2013 to 2025 or 2050, OECD countries

	Health Care Cost Old Age Dependency Ratio (HCCOADR)		**Old Age Dependency Ratio (OADR)**	
Country	**2025**	**2050**	**2025**	**2050**
Australia	22.7	42.1	45.2	71.1
Austria	13.1	46.6	44.1	76.6
Belgium	12.7	42.5	43.9	66.8
Canada	42.7	72.1	69.6	90.3
Chile	29.0	67.2	84.9	174.7
Czech Rep.	1.9	34.7	38.6	93.8
Denmark	19.3	26.4	30.9	39.0
Estonia	2.2	16.9	26.9	59.6
Finland	43.5	45.6	47.2	50.6
France	17.9	38.5	40.5	58.8
Germany	23.2	62.7	49.6	87.2
Greece	-6.2	54.0	35.5	102.1
Hungary	-5.3	13.2	25.6	74.1
Iceland	3.1	64.6	52.4	138.2
Ireland	21.3	54.5	58.4	107.7
Israel	5.1	25.4	33.6	68.1
Italy	-1.5	56.4	37.9	93.8
Japan	17.6	56.0	32.7	78.8
Korea, Republic of	31.5	141.8	117.3	288.3
Luxembourg	2.2	30.2	36.5	87.6
Mexico	-2.5	37.4	63.6	206.3
Netherland	37.7	76.1	60.0	84.9
New Zealand	30.7	51.1	54.6	78.7
Norway	9.9	28.4	34.5	57.2
Poland	22.8	54.6	73.2	149.2
Portugal	-1.2	54.8	42.4	128.1
Slovakia	13.6	50.7	70.6	163.4
Slovenia	20.5	77.4	62.5	122.9
Spain	-12.1	79.5	46.8	157.0
Sweden	12.0	12.7	22.2	28.0
Switzerland	13.8	27.5	33.2	55.0
Turkey	-5.3	34.3	62.7	196.4
UK	9.4	27.0	32.5	56.5
USA	37.5	50.3	57.3	69.0

Source: Authors' calculations based on United Nations (2013).

More research needs to be done to produce simple specification of how health care costs change as life expectancies increase. The health care cost old-age dependency ratio provides a small step in this direction. It is clear, however, that the old-age dependency ratio, which does not adjust at all for changes in longevity, should not be relied on to provide close approximations to likely increases in the health care costs associated with population aging.

Pension cost dependency ratios

Changes in pension ages and eligibility requirements are underway in most OECD countries. Some of those countries have already indexed their normal retirement age (i.e., the age of eligibility for a full old-age pension) to changes in life expectancy at old ages. For example, Sweden has a notional defined contribution (NDC) pension plan in which people can take their public pensions at any age beginning at 62 and receive a benefit adjusted for remaining life expectancy at that age. Norway, Poland, and Italy also have a version of an NDC. The Czech Republic has a pension system in which the normal retirement age is legislated to rise by 2 months per year for men and 4 months per year for women until the ages converge. Afterward, both retirement ages increase by 2 months per year. The UK has a normal retirement age that is planned to rise from 65 for men and 62 for women currently to 67 around 2027 and could well rise to 68 by the late 2040s (U. S. Social Security Administration n.d. for a more complete discussion of how pension plans are changing; OECD 2013; see OECD 2014). Given these and other ongoing and prospective changes in pension plans, the use of the conventional dependency ratio, with its assumption that all people aged 65 and above receive pensions, is inaccurate.

In a recent article (Sanderson & Scherbov 2015) we derived an inter- generationally equitable retirement age based on three criteria: (1) members of each cohort receive as much in pension payouts as they pay into the pension plan; (2) the generosity of the pension system, measured as the ratio of aver- age pension receipt to the incomes of people who pay into the pension system, after the pension tax, is the same for all cohorts; and (3) the pension tax is the same for all cohorts. We also show the relationship of that intergenerationally equitable retirement age to pension payouts in NDC pension systems.

Criterion (1) can be formulated as: $y \cdot r \cdot \left(T_{20} - T_\alpha\right) = p \cdot T_\alpha$, where y is the average annual income of cohort members, r is the pension tax rate, T_α is the number person-years lived from age 20 onward in the cohort's life table, T_α is the number of person-years lived from the intergenerationally equitable normal retirement age α onward, and p is the average annual pension payment. Criterion (2) can be represented as:

$p = \beta \cdot (1 - r) \cdot y$, where β, the generosity of the pension system, is the ratio of the annual pension payment to the income of the people contributing to the pension system, after the pension tax.

Combining the two criteria yields:

$$\frac{T_\alpha}{\left(T_{20} - T_\alpha\right)} = \frac{r}{\beta \cdot (1 - r)}$$

.

If $v_{a,i,t} = 1$ and r are fixed, this equation determines the intergenerationally equitable normal retirement age α because, at adult ages, the ratio $v_{a,i,t} = 1$ is monotonically decreasing with α.

Table 6 shows increases in intergenerationally equitable normal retirement ages between 2013 and 2050 based on UN forecasted life tables and the assumption that the intergenerationally equitable normal retirement age is 65 in 2013. The increases are insensitive to plausible changes in normal retirement ages in 2013. The increases in intergenerationally equitable normal retirement ages in Table 6 cluster around 3 years over the 37-year period, or somewhat less than a one-year increase in retirement age per decade. The increases in the intergenerationally equitable retirement age are illustrative. They would be almost identical had we started at other plausible full retirement ages in 2013. Similar increases, but with different country-specific normal retirement ages in 2013, can be found in Sanderson and Scherbov (2015).

In Table 7, we present percent changes in pension cost dependency ratios based on those intergenerationally equitable retirement ages and percent changes in old-age dependency ratios. Pension cost dependency ratios are a special case of equation (1) where $v_{a,i,t} = 1$ for ages at or above our intergenerationally equitable normal retirement age and 0 otherwise, and $w_{a,i,t} = 1$ for ages from 20 to the intergenerationally equitable retirement age and 0 otherwise.

The pension cost dependency ratio increases more slowly over time than the old-age dependency ratio. For example, the former increases by 31 percent in France from 2013 to 2050, while the latter increases by 59 percent. In the US, the increase in the former between 2013 and 2050 is 41 percent while the increase in the latter is 69 percent. Projections of pension cost de- pendency ratios for all OECD countries for 2013 through 2050 can be found at www.reaging.org/indicators.

The increases in the intergenerationally equitable normal retirement ages shown in Table 6 are not actual or legislated future changes. Pension arrangements vary widely from country to country. Longer-term analysis would benefit from a way of generating future normal retirement ages based on a set of known criteria that take into account changes in longevity. This is what our intergenerationally equitable normal retirement ages do. Table 6 showed plausible increases in intergenerationally equitable normal retirement ages in OECD countries over time. The use of those normal retirement ages is only one way to take into account the ongoing changes in pension arrangements. We cannot, in any case, ignore the fact that pension arrangements are changing. This is what the dependency ratio and the old-age dependency ratio do. When changes in pension arrangements were uncommon and there were no other options, the use of the dependency ratio and the old-age dependency ratio were the best that could be done under the circumstances. But we no longer need to rely on the old-age dependency ratio for analysis of the effects of age structure change on pension costs.

Prospective old-age dependency ratios

The term old-age dependency ratio conflates two concepts: old age and de- pendency. Earlier we provided a measure of financial dependency based on the direction of the flow of net transfers. Here we discuss the concept of old age. Following Ryder (1975), our measure of who is old is based on how close people are to the end of their lives. In this article and in our earlier work (Lutz et al. 2008; Sanderson & Scherbov 2013; Sanderson & Scherbov 2007; Sanderson & Scherbov 2005), we define people as being old when they are in age groups in which remaining life expectancy is 15 years or less. We call measures based on adjustment for differences in life expectancy “prospective” measures. We would obtain similar dynamics for our prospective measures if we had defined the thresh- old of old age as the age when remaining life expectancy was 10 years or any other plausible choice. We

Table 6. Increase (in years) in the intergenerationally equitable normal retirement age from 2013 to 2050, OECD countries

Country	Increase in Intergenerationally Equitable Normal Pension Age
Australia	2.8
Austria	3.0
Belgium	2.9
Canada	2.6
Chile	3.4
Czech Rep.	3.2
Denmark	2.9
Estonia	3.0
Finland	2.8
France	2.9
Germany	3.0
Greece	2.8
Hungary	3.2
Iceland	3.2
Ireland	2.8
Israel	2.9
Italy	3.1
Japan	3.0
Korea, Republic of	4.3
Luxembourg	3.1
Mexico	3.3
Netherland	2.7
New Zealand	2.7
Norway	2.6
Poland	3.2
Portugal	3.2
Slovakia	3.1
Slovenia	2.8
Spain	2.9
Sweden	2.8
Switzerland	2.8
Turkey	4.0
UK	2.8
USA	2.5

Source: Authors' calculations based on United Nations (2013).

chose 15 years because it was the remaining life expectancy of 65-year-olds in many low-mortality countries around 1970. In Table 8, we compare changes from 2013 to 2030 in the prospective old-age dependency ratio and the conventional old-age dependency ratio for OECD countries. Prospective old-age dependency ratios are a special case of equation (1) where $w_{a,i,t} = 1$ for ages at or above our old age threshold of being in an age group with a remaining life expectancy of 15 years or less and 0 otherwise, and $w_{a,i,t} = 1$ for ages from 20 to the old-age threshold and 0 otherwise.

Table 7. Percent change in the pension cost dependency ratio based on intergenerationally equitable retirement ages and percent change in the old-age dependency ratio from 2013 to 2025 or 2050, OECD countries

	Pension Cost Dependency Ratio (PCDR)		Old Age Dependency Ratio (OADR)	
Country	**2025**	**2050**	**2025**	**2050**
Australia	31.3	39.8	45.2	71.1
Austria	26.2	43.6	44.1	76.6
Belgium	27.9	36.6	43.9	66.8
Canada	53.3	58.3	69.6	90.3
Chile	57.8	113.6	84.9	174.7
Czech Rep.	23.2	53.3	38.6	93.8
Denmark	16.3	16.0	30.9	39.0
Estonia	13.1	23.6	26.9	59.6
Finland	33.2	23.5	47.2	50.6
France	26.6	31.4	40.5	58.8
Germany	30.8	51.8	49.6	87.2
Greece	21.1	66.5	35.5	102.1
Hungary	12.9	35.9	25.6	74.1
Iceland	33.4	84.6	52.4	138.2
Ireland	43.1	69.8	58.4	107.7
Israel	20.8	37.5	33.6	68.1
Italy	21.5	61.0	37.9	93.8
Japan	20.5	48.2	32.7	78.8
Korea, Republic of	77.4	187.2	117.3	288.3
Luxembourg	19.5	50.6	36.5	87.6
Mexico	40.8	138.3	63.6	206.3
Netherland	43.2	55.4	60.0	84.9
New Zealand	38.8	48.4	54.6	78.7
Norway	22.1	32.1	34.5	57.2
Poland	53.7	84.6	73.2	149.2
Portugal	24.8	80.8	42.4	128.1
Slovakia	51.8	100.1	70.6	163.4
Slovenia	45.5	80.0	62.5	122.9
Spain	30.3	111.9	46.8	157.0
Sweden	10.7	6.6	22.2	28.0
Switzerland	19.4	27.7	33.2	55.0
Turkey	33.0	111.0	62.7	196.4
UK	17.4	27.6	32.5	56.5
USA	42.7	41.1	57.3	69.0

Source: Authors' calculations based on United Nations (2013) and data underlying Table 6.

The prospective old-age dependency ratios generally increase less rapidly than the old-age dependency ratios. For example, the former increases by 11.3 percent in Germany, while the latter increases by 49.2 percent. In Finland, on the other hand, the increases in the two ratios are identical. Analysts who wish to assess the proportion of the population who are old no longer need to rely on the assumption that people always become old at age 65 regardless of place or time. Prospective old-age dependency ratios for all UN countries of the world from 1950 to 2100 can be found at www.reaging.org/indicators.

In an earlier section, we provided a measure of financial dependency based on the receipt of net transfers from others. Older people became financial dependents after the older transfer transition age. In this section, we discussed a method of classifying people as old based on their remaining life expectancy. In Table 9, we compare the age at which people become financially dependent and the age at which they become old. In OECD countries, people generally become financially dependent before they become old. For example, in Austria in 2000, people became financially dependent at age 58, while they became old at 69. In some developing countries, the situation was reversed and people became old before they became financially dependent. For example, in India in 2004, people became financially dependent at 70, while they became old at 62. People who are old need not be financially dependent and vice versa.

The dependency ratio has been used in studies of the demographic dividend, where it is said to represent the ratio of nonworking to working people (Bloom et al. 2007; Bloom et al. 2000; Kelley & Schmidt 2005). Those studies required ratios that were computed over a long period of time and for many countries, and the dependency ratios produced by the United Nations provided them. Now, however, the prospective dependency ratio has been computed and published for the same countries over the same time period using the same underlying data on population age structure. A test of the usefulness of the dependency ratio compared with the prospective dependency ratio for the study of the effects of age structure change on economic growth found that the prospective dependency ratio produced more accurate medium- and long-term forecasts (Crespo Cuaresma et al. 2014). One study is certainly not enough to prove that it is preferable to use prospective dependency ratios rather than conventional ratios in studies of economic growth. Even so, at this point, one cannot argue that the dependency ratio is clearly the best measure to use in economic studies. There is reason to entertain the possibility that we have been overly dependent on it.

Conclusions

It is normal in science to measure things as best we can. Over time, less accurate measures give way to more accurate ones. In the study of population aging, the dependency ratio and its components were developed in an era when far fewer data were available than they are today. Demographic methodology has also improved so that we can now conceptualize aspects of population aging separately from one another. In the current environment, we should try to use the best possible measures of the various facets of population aging, and, as we showed above, this will often mean less use of the dependency ratio.

This article has provided a wider and more focused set of options for analysts interested in measuring and forecasting population aging. We have put data on the economic support ratio, the health care cost old-age dependency ratio, the pension cost dependency ratio, and the prospective old-age dependency ratio on www.reaging.org/indicators. The data there are fully compatible with the population assumptions made in the UN's *World Population Prospects, 2015 Revision*. We have chosen illustrative parameters,

Table 8. Percent increase in the prospective old-age dependency ratio and the old-age dependency ratio from 2013 to 2030, OECD countries

Country	Prospective Old Age Dependency Ratio (POADR)	Old Age Dependency Ratio (OADR)
Australia	32.2	45.4
Austria	15.7	43.9
Belgium	21.2	44.1
Canada	47.5	69.5
Chile	44.7	84.8
Czech Rep.	31.4	39.0
Denmark	21.5	31.0
Estonia	12.4	27.1
Finland	47.3	47.3
France	24.1	40.3
Germany	11.3	49.2
Greece	12.0	35.5
Hungary	16.0	25.8
Iceland	31.7	52.9
Ireland	36.4	58.5
Israel	17.9	35.5
Italy	11.3	37.9
Japan	42.2	32.4
Korea, Republic of	52.0	117.0
Luxembourg	8.6	37.4
Mexico	35.9	63.3
Netherland	46.3	60.0
New Zealand	35.1	54.2
Norway	26.6	34.8
Poland	57.5	73.4
Portugal	15.8	42.4
Slovakia	50.4	70.8
Slovenia	37.8	62.4
Spain	15.5	46.9
Sweden	20.7	22.4
Switzerland	17.4	33.3
Turkey	22.7	62.6
UK	15.2	32.5
USA	45.3	57.3

Source: Authors’ calculations based on United Nations (2013).

such as cutoff ages and standardization dates, for the measures that we present here. We believe that those parameterizations are plausible. For readers for whom our assumptions are acceptable, data on the new measures are immediately accessible from that website. There may be purposes for which alternative parameterizations of the measures would be preferable. In those cases, our article provides both guidance and encouragement.

Table 9. Ages at becoming old and becoming financially dependent

Country/Region	Year	Age at Becoming "Old"	Age at Becoming Financially Dependent - Older Transfer Transition Age (OTTA)
Austria	2000	68.5	57.5
Brazil	1996	66.8	61.7
Costa Rica	2004	69.9	61.9
Finland	2004	69.2	59.1
Germany	2003	68.9	61.0
Hungary	2005	65.8	57.4
India	2004	62.0	70.4
Indonesia	2005	63.1	81.4
Japan	2004	72.0	62.2
Korea, Republic of	2000	66.9	62.8
Mexico	2004	68.8	70.5
Philippines	1999	62.2	70.6
Slovenia	2004	68.1	56.2
Spain	2000	69.4	60.3
Sweden	2003	69.5	63.6
Taiwan	1998	67.0	57.1
Thailand	2004	67.4	62.1
USA	2003	69.0	64.1

Source: Authors' calculations based on United Nations (2013) and Table 4.

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Faster Increases in Human Life Expectancy Could Lead to Slower Population Aging[1]

Warren C. Sanderson and Sergei Scherbov

Introduction

Human population aging is a multidimensional phenomenon. If differs from aging at the level of individuals. Each additional year individuals are alive, they grow one year older, but defining how populations age is much more complex (Sanderson & Scherbov 2005; Lutz et al. 2008; Sanderson & Scherbov 2010; Sanderson & Scherbov 2013). The study of human population aging can be divided into three components. The first is the change in the age structure of the population and the reasons for its change such as fertility and mortality. Age structure is usually measured using a few conventional measures such as the proportion of the population 65+ years old and the median age of the population. The second component is the change in the age-specific characteristics of people. For example, 65 year olds in the future are likely to have longer life expectancies, have higher average levels of education, and have better cognition than 65 year olds today. In some countries, 65 year olds today would be eligible for a full public pension, but 65 year olds in the future would not be. Older people in the future will have levels of many characteristics exhibited by younger people today. The third component of the study of human population aging is the interaction between changes in age structures and changes in the age-specific characteristics of people.

Population aging is widely discussed (European Commission 2012; United Nations 2013a), but those discussions usually focus solely on age structure and omit consideration of the changing age-specific characteristics of people. An ex- ample of this is the United Nations' *World Population Ageing 2013* (United Nations 2013a), which provides much of the data currently used in studies of population aging. Those data, which are computed for all countries of the world at 5-year intervals from 1950 to 2100, are based solely on age structures. In that volume, the UN categorizes people as being old when they reach age 60. It does not matter that 60 year olds in 1950 are likely to be very different from 60 year olds in 2100.

Many studies of population aging focus on specific countries and make forecasts over many decades. Over these long spans of time of characteristics of older people can change consider- ably. 60 year olds, for example, could have become healthier (Robine et al. 2013), have longer life expectancies (Christensen et al. 2009; Vaupel 2010; United Nations 2013b; United Nations 2013a), have better cognition (Skirbekk et al. 2013) and have become less dependent upon others for their daily care (Robine et al. 2013). Sixty-five is sometimes used as an old age threshold, because in some countries it was the age at which some people could be eligible for a full state pension. However, in most OECD countries normal pension ages are now in the process of changing. For example, the normal pension age in the United States used to be 65. Now it is 66 and it is scheduled to rise to 67. Assessing the pension burden based on a fixed age of 65 would produce a misleading result.

In the US, Medicare, a form of national health insurance for older people, begins covering people at age 65. In most other OECD countries, 65 is not an especially important

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age in terms of health care costs paid by the government. Health care costs depend on age, but they are much higher in the last years of life (Miller 2001). As life expectancy increases, those last years of life happen later and later. Ignoring this could produce distorted figures. Analyses of the speed of population aging that disregard the changing characteristics of people are incomplete and potentially, for that reason, they can produce biased findings.

The first step in our analysis is the measurement of the speed of population aging using two measures that take into account changes in age structure, changes in the characteristics of people, and the interaction of those two. We call these the prospective proportion of the people who are old and the prospective median age. The second step is the comparison of the speed of aging using these more complete measures with the speed of aging using the conventional pro- portion of the population who are considered old and the conventional median age. The final step is the discussion and interpretation of our findings.

Ryder (1975) challenged the conventional view in which people are classified as old based on a fixed chronological age. In the study of aging, he argued that it would be preferable to consider people as old not based on their chronological ages, but instead on their expected remaining lifetimes. He argued that those expected lifespans were a better reflection of older people's health, dependence on others, and their general level of functioning than their chronological ages. Ryder's insight has been independently rediscovered (Fuchs 1984; Sanderson & Scherbov 2005), applied (Jacob S. Siegel & Maria Davidson 1984; Siegel & Olshansky 2008; Siegel et al. 1993) and elaborated (Sanderson & Scherbov 2005; Lutz et al. 2008; Sanderson & Scherbov 2013; Sanderson & Scherbov 2014; Sanderson & Scherbov 2010; Sanderson & Scherbov 2008). This paper is based on those elaborations. In particular, here we use a measure of age, called prospective age, which is based on remaining life expectancy. That literature demonstrates that, in the study of population aging over a long time period and across countries with quite different mortality conditions, it is preferable to use a definition of age based on remaining life expectancy than one based on chronological age.

In this paper, we show a previously unobserved implication of the use of prospective age instead of chronological age. When prospective age is used, increases in measures of population aging are slower when the pace of life expectancy improvements is faster. This is the opposite of the conventional view that faster increases in life expectancy will cause the speed of aging to increase.

Methods

The population projections made in this paper use the cohort component method (Preston et al. 2000) The required inputs are initial distributions of populations by age and sex in the base year and assumptions about future age-specific rates of fertility, mortality, and migration. In Scenario 3, we use the initial population distributions and the future age-specific rates that were used in making the projections in the European Demographic Data Sheet 2014 (VID 2014a). The initial population age structures used there come from Eurostat (European Commission 2014). The forecasts of age-specific rates come from a study that utilized both historical data and expert opinion (Lutz et al. 2014). Details of the methodology can be found at European Demographic Data Sheet 2014: Learn more about the data, methods and assumptions used in the population projections (VID 2014c). Detailed notes can be found at the Vienna Institute of Demography website (VID 2014b) by clicking on the link to "Sources and notes".

Scenario 1 uses the same initial population distributions, age-specific fertility and migration assumptions as Scenario 3, but keeps age-specific survival rates constant. Scenario 2 was created on the assumption that changes in life expectancy at birth from 2013 onward were half of those in Scenario 3. This was done separately for men and women. Age-specific mortality rates in Scenario 2 and 3 were obtained from scenarios specified with respect to life expectancy at birth, using a Brass relationship model (Brass 1971). Table 1 lists the assumptions for all three scenarios.

We compare the speed of population aging across those three scenarios using four measures. Two of them measure changes in the proportion of the population who are "old". In the conventional approach, the threshold age at which people as assumed to become "old" is fixed, using at age 65. In contrast, we define the prospective old age threshold, which takes changes in longevity into account is variable. Here, as in our previous papers (citations here), we use an old age threshold the age at which remaining life expectancy first falls below 15 years. This is roughly the remaining life expectancy of people in many low mortality countries in the 1960s-70s (University of California, Berkeley & Max Planck Institute for Demographic Research 2014). For example, using the prospective old age threshold French women would be classified as being old beginning at age 58.4 in 1900, at age 64.8 in 1956, and at age 74.6 in 2012 (University of California, Berkeley & Max Planck Institute for Demographic Research 2014).

Prospective median ages are the ages in 2013 where remaining life expectancy is the same as at the median age in the indicated year. More formally, Let $ma(t)$ be the median age of a population in year *t*, *e(a,t)* be remaining life expectancy at age *a* in year *t* and let the remaining life expectancy at the median age be $e(ma(t),t)$. The prospective median age is the age in the base year (2013, in this case) with the same remaining life expectancy as observed at the median age in year t($e^{-1}(e(ma(t),t),2013$)).

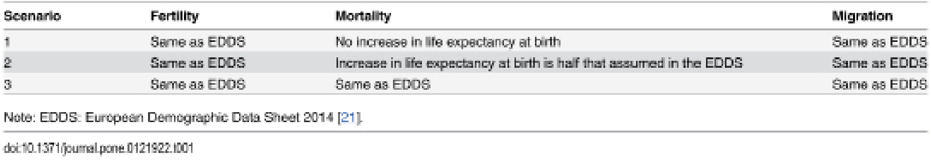
The threshold ages for being categorized as old are defined as those ages where remaining life expectancy is 15 years or less. Let $a_{old}(t)$ be the old age threshold in year *t.* The old age threshold, then is defined as $a_{old}(t) = e^{-1}(15,t)$.

Results

We use three scenarios for population projections (see Table 1). The baseline scenario (Scenario 3) is the one used elsewhere to make population forecasts from 2013 to 2050 for all European countries (VID 2014a). Scenario 1 is identical to Scenario 3 except that life expectancies at birth are kept constant at their 2013 levels. In Scenario 2, gains in life expectancy at birth from 2013 onwards are half as large as in Scenario 3. Thus, the speed of life expectancy increase rises with the scenario number. The derived life expectancies at age 65 for all European countries for 2013, 2030, and 2050 are presented in S1 Table. The average pace of increase of life expectancy at 65 in all European countries is around 0.7 years per decade in the second scenario and around 1.4 years per decade in the third.

Table 2 shows the proportions of the German population, for the years 2013, 2030, and 2050, who are old using as the old age threshold: (1) age 65, and (2) the age when remaining life expectancy first falls below 15 years. Figures were initially computed separately for men and women and then combined. Table 2 shows that faster gains in life expectancy increase the measured speed of aging using the conventional measure, but decrease it when changes in longevity are taken into account. In 2050, in Scenario 1, with no life expectancy increase, the proportion of the German population 65+ years old would be 0.278. With the expected increase in life expectancy, but unaltered fertility and mortality rates, the proportion grows

Table 1. List of Assumptions for all Three Scenarios.



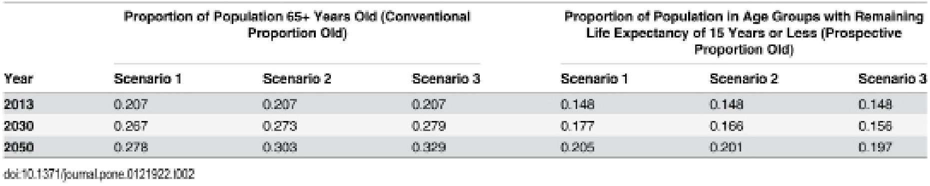
Scenario	Fertility	Mortality	Migration
1	Same as EDDS	No increase in life expectancy at birth	Same as EDDS
2	Same as EDDS	Increase in life expectancy at birth is half that assumed in the EDDS	Same as EDDS
3	Same as EDDS	Same as EDDS	Same as EDDS

Note: EDDS: European Demographic Data Sheet 2014 [21].

doi:10.1371/journal.pone.0121922.t001

Note: EDDS: European Demographic Data Sheet 2014 [21].

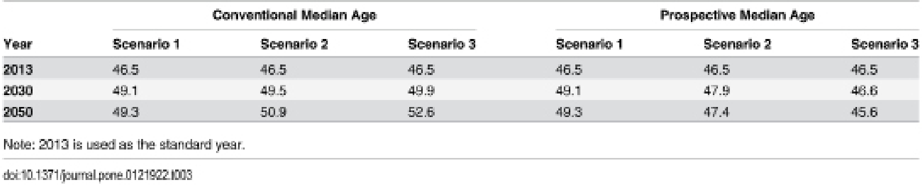
Table 2. Conventional and Prospective Proportions Old, Germany 2013, 2030, and 2050: Three Scenarios of Life Expectancy Increase (both sexes).



	Proportion of Population 65+ Years Old (Conventional Proportion Old)			Proportion of Population in Age Groups with Remaining Life Expectancy of 15 Years or Less (Prospective Proportion Old)		
Year	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2013	0.207	0.207	0.207	0.148	0.148	0.148
2030	0.267	0.273	0.279	0.177	0.166	0.156
2050	0.278	0.303	0.329	0.205	0.201	0.197

doi:10.1371/journal.pone.0121922.t002

Table 3. Conventional and Prospective Median Ages, Germany, 2013, 2030, and 2050 for 3 Scenarios of the Speed of Life Expectancy Increase (females)



	Conventional Median Age			Prospective Median Age		
Year	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2013	46.5	46.5	46.5	46.5	46.5	46.5
2030	49.1	49.5	49.9	49.1	47.9	46.6
2050	49.3	50.9	52.6	49.3	47.4	45.6

Note: 2013 is used as the standard year.

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Note: 2013 is used as the standard year.

to 0.329. In Scenario 3, more elderly people survive and the proportion 65+ increases. When prospective age is used, the threshold age at which people are categorized as old changes over time. The prospective proportion old is 0.237 in Scenario 1. In Scenarios 2 and 3 it is lower, 0.218 and 0.199 respectively. The proportion of the population old falls with increases the speed of life expectancy gains.

We provide data for only one country in the text because our focus is on the relationship between the speed of population aging and the speed of life expectancy change. If we had included data for several countries in Table 2, it would have shifted our focus to the differences between the countries. For completeness, we provide the same data in S2 Table. All the countries in S2 Table exhibit the same relationship between the measured speed of population aging and the speed of life expectancy change that we observe for Germany in Table 2.

The computation of the conventional and the prospective proportion old requires the specification of a criterion which separates old people from those who are not old. A common measure of population aging that does not require a separation criterion is the median age.

In Table 3, we show the conventional median age and prospective median age of women in Germany under the three scenarios for 2013, 2030, and 2050. The prospective median age is the age in the base year (in this case 2013) where remaining life expectancy is the same as at the median age in the indicated year. Thus, in addition to changes in the conventional median age, the prospective median age takes into account how life expectancy at the conventional median age is changing. As life expectancy increases it is possible that, simultaneously, the conventional median age grows older and remaining life expectancy at that median age grows longer (Sanderson & Scherbov 2005). Data are provided only for a single sex in order to simplify and clarify the presentation and the interpretation of the results. Figures for men and for both sexes combined tell exactly the same story.

The conventional median age and the prospective median age are identical in Scenario 1, where there is no increase in life expectancy. In 2013, the median age of the German population was 46.5 years. If age-specific survival rates remained constant at their 2013 levels, the median age is forecast to rise to 49.3 in 2050 because of the age structure of the German population in 2013 and assumptions about fertility and migration rates. If, in addition, age-specific survival rates were to increase as in Scenario 3, the median age would rise another 3.3 years to 52.6 in 2050. This example illustrates that when the conventional median age is used as an indicator of aging, faster increases in life expectancy appear to cause faster increases in aging.

When the prospective median age is used as an indicator of aging, Table 3 demonstrates the opposite result. If there would be no increase in life expectancy between 2013 and 2050, the prospective median age would rise 2.8 years from 46.5 to 49.3. If life expectancy increases, as in Scenario 3, the prospective median age actually decreases. The prospective median age in Scenario 3 in 2050 is 3.7 years lower than it would be under the assumption of no life expectancy increase. Here again faster increases in life expectancy lead to slower increases in measured population aging. This pattern, again, is the same for all European countries (S3 Table).

The main findings in Table 2 and Table 3 are summarized in Figs. 1 and 2. In Fig. 1, we show the forecasted relationship between the change in the proportion of the population who are categorized as being old and the speed of life expectancy change in Germany over the period 2013 to 2050. We show the relationship for the conventional measure of the proportion old where the old age threshold is fixed at age 65 and for the prospective measure where the old age threshold is defined as the age at which remaining life expectancy is 15 years. As the speed of life expectancy change increases (going upwards from Scenario 1 to Scenario 3), the change in the proportion of the population categorized as old always increases when the conventional measure is used, but always decreases when the prospective measure is used.

In Fig. 2, we show the forecasted relationship between the change in the median age of the population and the change in the speed of life expectancy change in Germany over the same period. The relationship is shown for the conventional median age and for the prospective median age. As the speed of life expectancy change increases (going upwards from Scenario 1 to Scenario 3), changes in the conventional median age increase, but changes in the prospective age decrease. In both Figures, it can be seen that faster increases in the speed of life expectancy result in slower changes in prospective measures of population aging. This is just the opposite of the result when conventional measures are used.

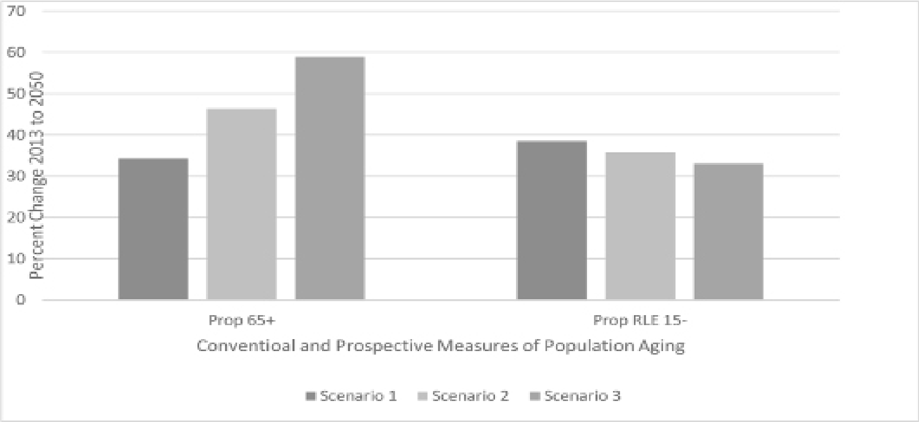

Figure 1. Percentage Increase in Proportions “Old” from 2013 to 2050, Using Measures Unadjusted and Adjusted for Longevity Change, Germany.

Note: Prop 65+ is the proportion of the population 65+ years old. It is the conventional measure of the proportion of the population who are old. Prop. RLE 15- is the proportion of the population who are in age groups with remaining life expectancy of 15 years or less. It is the prospective measure of the proportion of the population who are “old”. The percentage increases in the proportions “old’ are one measure of the speed of aging. When the prospective measure of the speed of aging is used faster increases in life expectancy lead to slower increases in population aging.

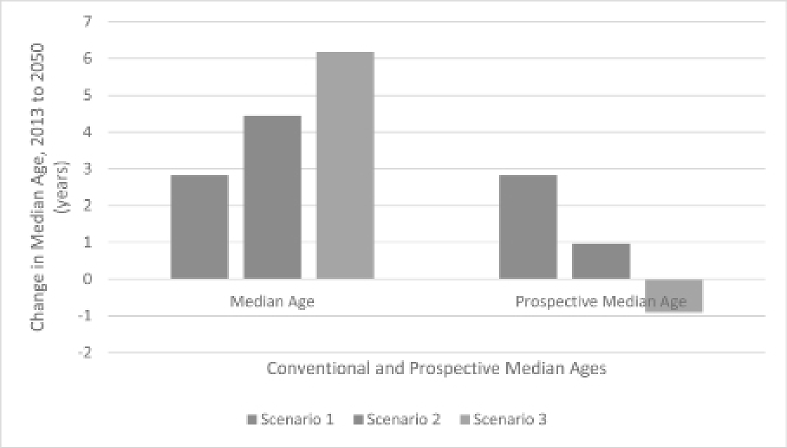

Figure 2. Changes in Median Age from 2013 to 2050 Using Measures Unadjusted and Adjusted for Longevity Increase, Germany.

Note: See definition of prospective median age in the text. Changes in the median age are one measure of the speed of aging. When the prospective median age is used the speed of aging decreases when life expectancy increases is faster.

Discussion

We present data here on the two of most commonly used measures of population aging, the proportion of the population old and the median age of the population for 39 European countries for 2013, 2030, and 2050 in S2 Table and S3 Table. These countries, which include Germany, Iceland, Moldova, and Russia, exhibit a wide variety of demographic conditions and in all these cases the prospective measures indicate that faster increases in life expectancy lead to slower population aging.

The main difference between the prospective and conventional measures of the proportion of the population who are old is not that they use different old age thresholds. It is that, in the case of the prospective measure, the old age threshold changes over time as life expectancy changes.

Both the conventional old age threshold, which is fixed at age 65, and the variable one used here have an element of arbitrariness. Conventional measures of population aging could categorize people as becoming old beginning at age 60, 65, or 70. Prospective measures could categorize people as becoming old, when they are in age groups with 10, 15, or 20 years of remaining life expectancy. The conclusions with respect to the relationship between the speed of life expectancy increase and the measured speed of population aging presented above are robust to any plausible changes in those values. For example, if we had computed tables showing the speed of aging using a fixed old age threshold of 60 and a prospective old age threshold of 10 remaining years of life, the major trends would have been the same.

The mechanics of the computation of prospective median age and the proportion old are quite different. The life table for each country in 2013 is used as a standard in the calculation of prospective median ages. It does not matter which year is chosen for the standard or even if one of the standards was used for all the countries. Faster increases in life expectancy would still lead to slower changes in measures of population aging.

The prospective median age is an indicator of the median remaining lifespan of the population. When we compare populations in Scenario 1, with no increase in longevity, with those in Scenario 3, we see that the chronological median age of the populations in Scenario 3 are higher than those in Scenario 1, but that the median remaining life expectancies are also higher. In- creases in life expectancy gains make populations relatively younger in the sense of having a longer median remaining lifespan.

The connections between life expectancy and aging presented here are important for understanding the future speed of aging. There are numerous data sources that provide information on the extent and speed of aging in various countries (Anon n.d.; Anon n.d.). Virtually all of these cite the UN measures that assume old age begins at 60 or 65, but those measures are incomplete. There are two aspects of aging that need to be incorporated into studies of population aging, changes in the age structures of populations and changes in the characteristics of people.

One way in which population aging can occur is that fertility falls and everything else about the population, including life expectancy, remains the same. This is a situation in which the age structure of the population changes, but the age-specific characteristics of people remain the same. In this case, the conventional and prospective proportions of the population who are old and the conventional and prospective median ages of the population would rise, not because there are more elderly people, but because there are fewer young people. Faster decreases in fertility, everything else being equal, would result in faster increases in the measures of aging, but conventional and prospective median ages would remain identical. When population aging happens only because of reductions in fertility, but not because of changes in life expectancy, the conventional measures, based solely on chronological age work well.

Population aging in most European countries in the last half century has not been the result solely of decreases in fertility. Life expectancy has also risen at each older age. The prospective approach takes this into account.

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Probabilistic Population Aging[1]

Warren C. Sanderson, Sergei Scherbov and Patrick Gerland

Introduction

Population aging poses widely discussed policy challenges (United Nations 2015a; He et al. 2016, p.2015; WHO & US National Institute of Aging 2011; Lee & Mason 2014). The United Nations publishes probabilistic forecasts of three measures of population aging, the old-age dependency ratio, the total dependency ratio, and the potential support ratio (United Nations 2015b). These provide information about the likely extent and uncertainty of population aging on the national level and so provide the basis for policy and academic analyses.

Probabilistic population forecasts were motivated by Keyfitz (1981). Keyfitz wrote:

"Demographers can no more be held responsible for the inaccuracy in forecasting population 20 years ahead than geologists, meteorologists, or economists when they fail to announce earthquakes, cold winters, or depressions 20 years ahead. What we can be held responsible for is warning one another and our public what the error of our estimates is likely to be." (p. 579).

There is now an extensive literature of probabilistic forecasting (Keilman & Pham 2004; Lee & Carter 1992; Raftery et al. 2012; Sevcikova et al. 2015; Lutz et al. 1997; Lutz et al. 2001; Lutz et al. 1999; Sanderson 2004; Keilman 2008; Keilman et al. 2002; Lee 1999; Lutz & Goldstein 2004). All the probabilistic measures of aging produced by the United Nations assume that the threshold of old age is a fixed chronological age, regardless of time, place, education, or other characteristics of people. Ryder (Ryder 1975, p.16) questioned this assumption. He wrote:

> "To the extent that our concern with age is what it signifies about the degree of deterioration and dependence, it would seem sensible to consider the measurement of age not in terms of years elapsed since birth but rather in terms of the number of years remaining until death."

Ryder suggested the old age threshold be defined on the basis of some plausible remaining life expectancy rather than any specific chronological age. Sanderson and Scherbov (Sanderson & Scherbov 2005; Sanderson & Scherbov 2013) extended and generalized Ryder's idea. They defined characteristic-equivalent ages as chronological ages at which a measure of some characteristic is held constant. We call the ages, that are obtained when life expectancy is the characteristic that is held constant, prospective ages and measures that use them prospective measures of population aging. In this paper, we merge two methodologies, probabilistic population forecasting based on a Bayesian hierarchical model (Raftery et al. 2012) and prospective ages to produce new probabilistic forecasts of aging.

New measures of population aging are useful because tomorrow's older people will not be like today's. They may well have longer life expectancies (Christensen et al. 2009; Vaupel 2010), better cognition (Bordone et al. 2015), better education (Scherbov et al. 2014), and fewer severe disabilities (Sanderson & Scherbov 2010). In most OECD countries, the labor

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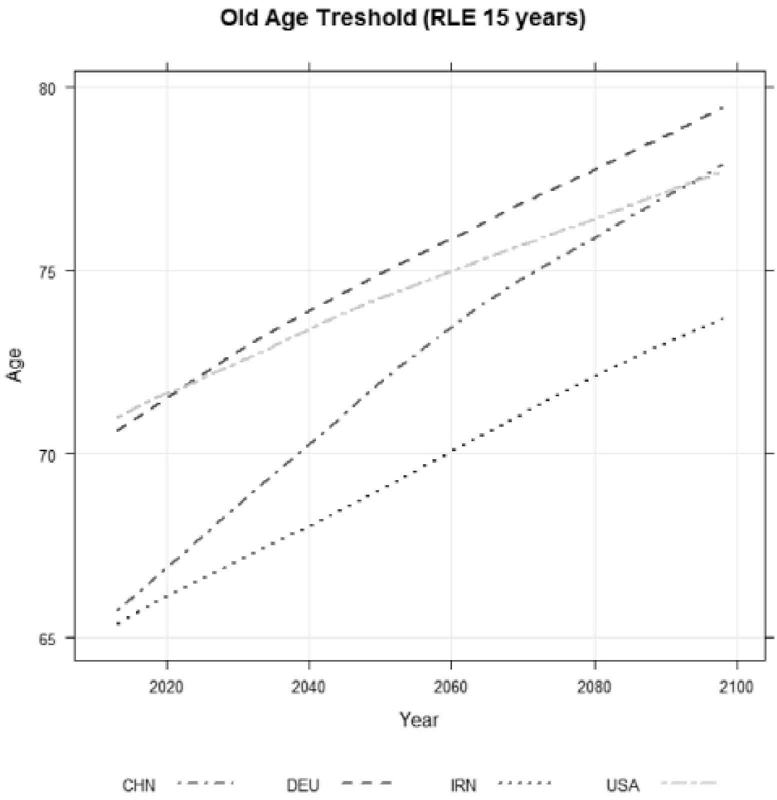

Figure 1. Old age threshold based on a remaining life expectancy of 15 years. Source: UN (2015) and authors' calcuations.

force participation of people 65+ years old is increasing (ILO 2011) as are the ages at which people can receive a normal national pension (OECD 2013; OECD 2014). Since changes in the characteristics of people are ignored in the conventional measures of aging, they become more outdated with the passage of time. The use of prospective ages is one way to create measures of aging that are more in line with observable changes.

Prospective ages can be used in a wide variety of contexts in the study of population aging. Here we use them in two ways. First, we follow Ryder and define the threshold of old age based on a remaining life expectancy rather than a fixed chronological age. We chose a remaining life expectancy of 15 years. That was the life expectancy at age 65 in many low mortality countries around 1970.

In Fig 1, we show estimated and forecasted old age thresholds based on a remaining life expectancy of 15 years for China, Germany, Iran and the US for the years 2013 through 2098. In 2013, the old age threshold was 66 in China and 72 in Germany. By 2098, the old age thresh- old is forecasted to increase to 79 in Germany and 77 in China.

In the second application of prospective ages we modify the conventional median age (Sanderson & Scherbov 2005; Sanderson & Scherbov 2013). Instead of reporting median ages in terms of chronological ages, we report them in terms of prospective ages.

Table 1. Median age, prospective median age, and remaining life expectancy at the median age: USA, 2013–2098.

country	year	Median Age (MA)	Prospective Median Age (PMA)	Remaining Life Expectancy at the Median Age (RLE at MA)
USA	2013	37.6	37.6	43.0
USA	2018	38.3	37.7	42.9
USA	2023	38.9	37.7	42.9
USA	2028	39.7	37.8	42.8
USA	2033	40.4	37.9	42.7
USA	2038	41.0	37.8	42.8
USA	2043	41.3	37.5	43.1
USA	2048	41.6	37.1	43.5
USA	2053	41.8	36.7	43.8
USA	2058	41.9	36.4	44.2
USA	2063	42.2	36.1	44.4
USA	2068	42.6	36.0	44.5
USA	2073	43.0	35.9	44.6
USA	2078	43.3	35.7	44.7
USA	2083	43.6	35.5	44.9
USA	2088	43.9	35.4	45.1
USA	2093	44.2	35.2	45.3
USA	2098	44.5	35.1	45.4

For example, Table 1 shows the median age and the prospective median age of the US population from 2013 to 2098, as well as the remaining life expectancy at the median age. In Table 1, we use the life table of the US in 2013 as a reference. The prospective median age standardizes the median age for changes in life expectancy. In particular, the prospective median age is the age in the reference life table where remaining life expectancy is the same as at the median age in the specified year. The median age in the US in 2013 was 37.6 years. At that time the remaining life expectancy of people 37.6 years old was 43.0 years. In 2098, the median age is forecasted to increase by 6.9 years to 44.5 and the remaining life expectancy is also expected to rise from 43.0 to 45.4. In 2013, the base year for the calculation of the prospective median age, people had a remaining life expectancy of 45.4 years at age 35.1. Therefore, the prospective median age in the US in 2098 is 35.1. People in the US at the median age in 2098 are expected to be older than the people at the median age in 2013 but, nevertheless, have a longer remaining life expectancy.

Materials and methods

We drew for each country a systematic subsample of one thousand random trajectories from the 10,000 that were the basis of the UN's 2015 probabilistic population projections. Each trajectory included the age structure of the population at 5 year intervals starting in 2015 and abridged life tables for five year intervals from 2015–2020 to 2095–2100 combining data for both sexes. Conventional measures were computed at the midpoint of the 5 year intervals and prospective measures were computed applying the corresponding life tables to those populations.

The old age threshold used in the computation of the prospective proportion of the population who are old and the prospective old age dependency ratio is derived from the equation:

$$oat_{j,t} = e_{j,t}^{-1}(15),$$

where $oat_{j,t}$ is the old age threshold in country *j* in year *t* and $e_{j,t}^{-1}(15)$ is the age in the life table for country *j* in year *t* where remaining life expectancy is equal to 15 years.

The prospective median age in country j in year t is derived from the equation:

$$pma_{j,t} = e_{j,2013}^{-1}[e_{j,t}(ma_{j,t})],$$

where $pma_{j,t}$ is the prospective median age in country *j* in year *t*, $t, ma_{j,t}$ is the median age in country *j* in year *t*, $e_{j,t}(ma_{j,t})$ is the life expectancy in the life table for country *j* and year *t* at the median age of the population in that year, and $e_{j,2013}^{-1}[e_{j,t}(ma_{j,t})]$ is the age in the country's life table of 2013, where remaining life expectancy is the same as at the median age in year *t*.

Results

Figs 2–5 present measures of population aging for four countries, China, Germany, Iran, and the US. Each figure has six panels. The panels on the left-hand side show three measures of aging that are based on chronological ages. The topmost shows the probabilistic distribution of the proportion of the population who are 65+ years old. The middle graph presents the distribution of the old age dependency ratio (OADR), defined as the ratio of people 65+ years old to those 20–64 years old. The bottom graph shows the distribution of the median age of the population.

The graphs on the right side present analogous measures that utilize prospective ages. In the topmost graph the onset of old age is defined using a prospective age instead of the fixed age 65. In that graph, the threshold of old age is set to the age at which remaining life expectancy was 15 years. In the middle graph on the right, the prospective old age dependency ratio is defined as the ratio of people at or above the prospective threshold age to the number of people between 20 and the prospective threshold age. The prospective median age in the bottom right graph is the age in 2013 (taken here as the base year) where remaining life expectancy is the same as at the median age in the indicated year.

Prospective proportions of the population who are old and prospective old age dependency ratios (POADR) are lower in 2013 than their counterparts that use age 65 as the old age threshold because the age at which remaining life expectancy was 15 years was above age 65. The prospective measures also grow less rapidly. The probabilistic forecasts also reveal a difference in the standard deviations of the forecasts.

The standard deviations of the forecasts of the prospective proportion of the population who are old and the prospective old age dependency ratios (POADR) are less than their counterparts that do not use prospective ages. In Germany and the US, the standard deviation of the POADR in 2058 was 0.01, while the standard deviations of their OADRs in that year were 0.05 and 0.03 respectively. In China, the analogous numbers are 0.03 for their POADR and 0.06 for their OADR. In the case of Iran the difference between the standard deviation of the POADR and the OADR is smaller, being 0.04 and 0.05 respectively.

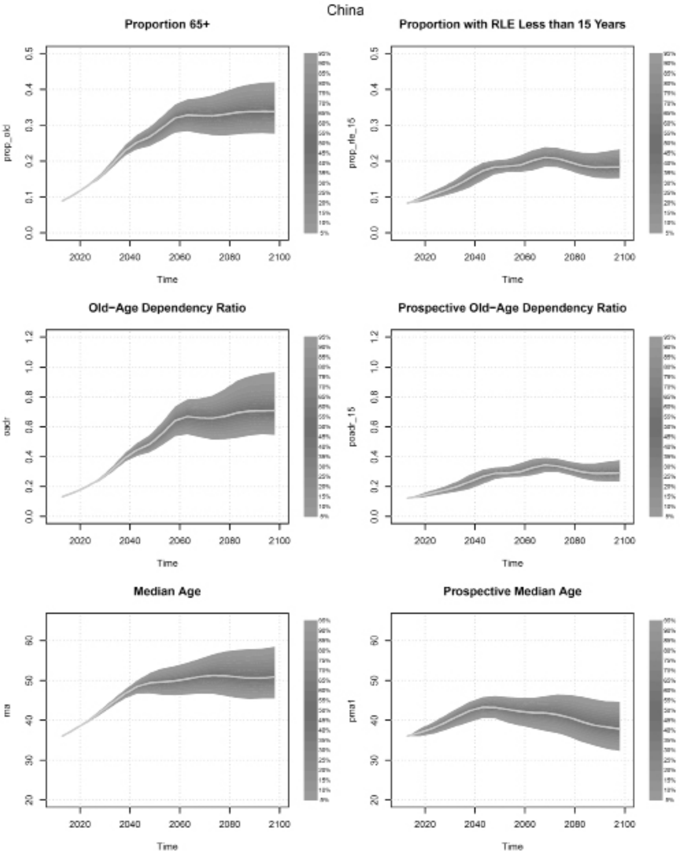

Figure 2. Probabilistic forecasts for three aging measures based on chronological ages and three based on prospective ages, China 2013–2098. Source: UN (2015) and authors' calculations.

The standard deviations of the POADR remain relatively small even to the end of the century. In 2098, the standard deviation was 0.05 for China, 0.03 for Germany, and 0.02 for the US. Indeed, in the US, the 90 percent prediction interval for the POADR in 2098 was between 0.18 and 0.25. In Iran, uncertainty with respect to the POADR in 2098 was much higher than in the other three countries. The standard deviation there was much higher, 0.13.

The distributions of the four measures look different for Iran than for the other three countries. Iran experienced one of the most rapid decreases in fertility in history during the 1980s (Abbasi-Shavazi et al. 2009). The resulting waves in the population age structure propagate over time and produce the uncertainties that we see in Fig 4, which are larger than for any of the other countries. China also had a rapid fertility decline, which occurred somewhat earlier than Iran's, which lead to an irregular age distribution, as well. The large irregularities in the age structures in Iran and China contributed to the large observed uncertainties in the prospective measures.

Turning to the median age and the prospective median age, we see that while the median age either rises or remains roughly constant over time, the prospective median age

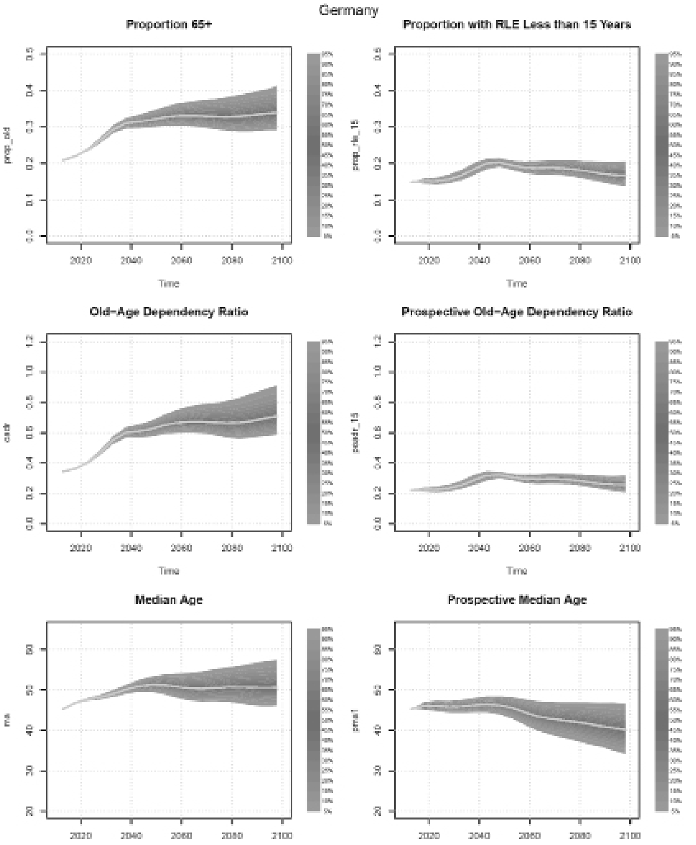

Figure 3. Probabilistic forecasts for three aging measures based on chronological ages and three based on prospective ages, Germany 2013–2098. Source: UN (2015) and authors' calculations.

actually falls. The decline begins earliest in the US, where the peak prospective median age is 37.8 at around 2038. The prospective median age then falls to 35.0 by 2098. The decline in prospective median age begins slightly later in Germany where it falls from 46.5 in 2043 to 40.1 in 2098.

The decline in China begins around 2048 and around 2073 in Iran. By 2098, Iran has the highest median age and prospective median age among the four countries. In contrast to the case for the OADR and the POADR, the standard deviations of the prospective median age tend to be about the same as for the median age.

Discussion

Each of the trajectories that we use is computed using assumptions about the paths of fertility and mortality rates. In the four countries that we are considering infant and child mortality rates are already quite low at our starting date in 2013, so most of the increase in life expectancy arises because of future increases in survival at upper ages. Some probabilistic trajectories will tend to have higher life expectancies and other lower ones. The life expectancies are auto-correlated, so that a trajectory with a higher than

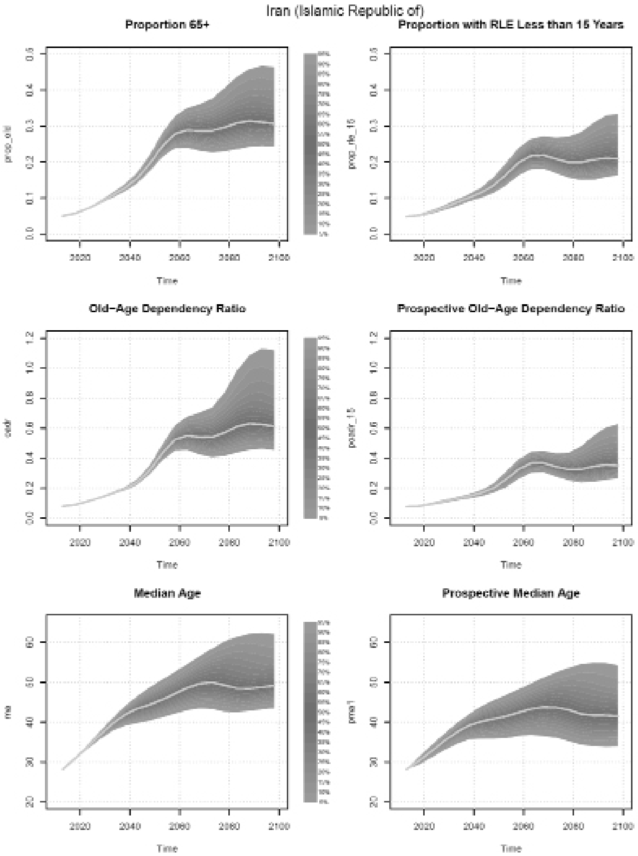

Figure 4. Probabilistic forecasts for three aging measures based on chronological ages and three based on prospective ages, Iran 2013–2098. Source: UN (2015) and authors' calculations.

average life expectancy in one year has a greater probability of having a higher than average life expectancy in the following year. On trajectories that, on average, have higher life expectancies, the number of people aged 65+ is higher and therefore, so is the proportion of the population 65+ and the old age dependency ratio.

When we consider the prospective proportion of the population who are old and the prospective old age dependency ratio, there is another factor at work. Populations with higher numbers of 65+ year olds have, on average, higher life expectancies, and, therefore, higher old age thresholds. Higher old age thresholds decrease both the prospective proportion old and the old age dependency ratio. Thus, higher life expectancies produce two offsetting effects on the prospective measures.

The same factors that affect the relationship between the OADR and the POADR affect the relationship between the median age and the prospective median age. One difference is that the prospective median age uses the median age as an input, while the POADR does not use the OADR as an input. Since the prospective median age uses the median age as an input, the distribution of median ages in a given year is one component of the distribution of prospective median ages. In addition to the uncertainty in the median age,

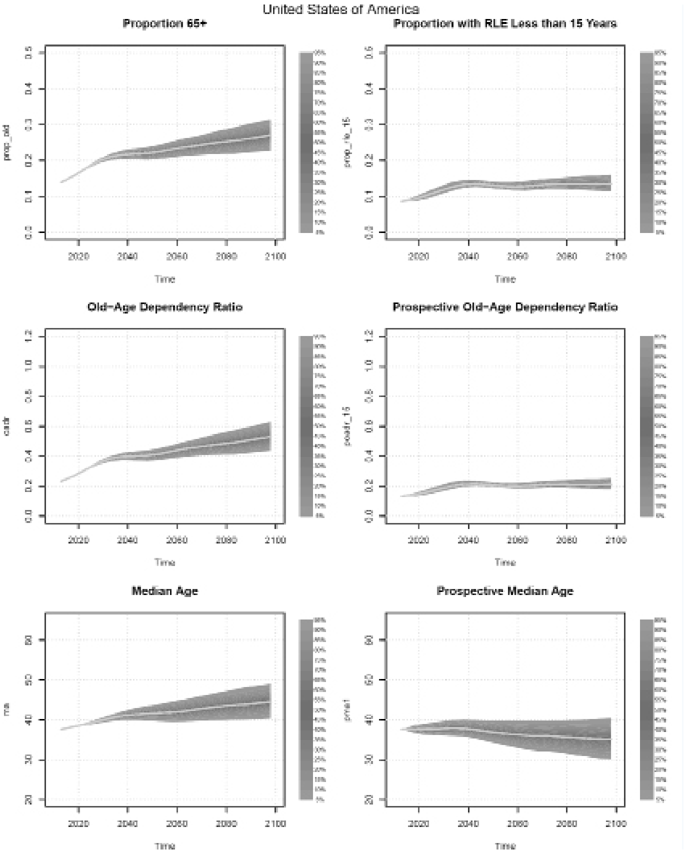

Figure 5. Probabilistic forecasts for three aging measures based on chronological ages and three based on prospective ages, USA 2013–2098. Source: UN (2015) and authors' calculations.

the prospective median age also is affected by variations in prospective ages resulting from differences in life tables.

We can draw several conclusions from this analysis. First, prospective measures of aging are both lower than their conventional counterparts and they increase more slowly or even decrease. Second, prospective measures generally have smaller standard deviations than those based only on chronological age.

The third conclusion is that most of the aging that we measure in China, Germany, and the US occurs between now and around 2040. In the case of Iran, it continues to around 2060. In Germany, the prospective old age dependency ratio is forecasted to be around 0.22 in 2018. By 2038, the median prospective old age dependency ratio rises to 0.29 with a 90 percent prediction interval from 0.26 to 0.32. By 2098, the median prospective old age dependency ratio falls to 0.26 with a 90 percent prediction interval from 0.22 to 0.32. Put differently, in 2018, we would expect there to be around 4.5 people from age 20 to the old age threshold per person at or above the old age threshold. By 2038, when aging measures would nearly be at their maxi- mum, the 90 percent prediction interval is between 3.1 and 3.8.

The probabilistic forecasts show that it is highly likely that the prospective median age of the population of Germany and the US will be lower in 2098 than it is today. Even in China there is around a 50 percent chance that the prospective median age will be lower at the end of the century than it is today. It is possible that people's concern about the future is related to the number of additional years they expect to live. Lower prospective median ages in 2098 than now indicate that the people at the median age will have even more years of additional life ahead of them than people at the median age have currently.

Policy-makers and others who want to understand and prepare for the future need appropriate data to guide them. Measures of population aging that do not take the changing characteristics of people into account do not provide this. Probabilistic prospective measures of population can provide the kinds of information that is needed.

Acknowledgments

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4 Sustainable Development and Policy Implications

Introduction

Alexia Fürnkranz-Prskawetz

Changes in population structure are closely linked to questions of economic and environmental sustainability. Sergei Scherbov and his co-authors have contributed two important themes to this literature. For developed countries, they have studied the implications of aging populations on the electorate and retirement ages, while for developing countries, they have studied the link between high fertility, poverty, and land degradation. For both of these research agendas, Sergei has demonstrated how formal demographic methods can be applied to gain new insights into the complex interrelations between demographic structures and key economic/environmental processes.

As argued by many economists (e.g., Poterba 1998) and shown in political-economic models, the age structure of voters may influence the public transfer programs supported by the electorate. Demographers, for example, Preston (1984) have also argued that the age and household structure of a society is closely linked to age-specific transfer programs. Sergei together with Warren Sanderson (2007, this volume) took a novel approach to this literature. Instead of focusing only on the age structure of the electorate, they defined different characteristics of it, and they investigated how those characteristics changed over time depending on demographic change and policy reforms. For instance, the share of the voting age population receiving pensions will depend on the age structure of the population and also on the specific retirement ages inherent in any given pension policy. Similarly, the waiting time from the median age of the population to the normal retirement age will depend on demographic developments as well as on pension policies. The share of the voting age population receiving a pension can be reduced either by postponing the retirement age or by reforming the voting rules. Based on research by Demeney (1986) the mean age of the voting age population could be reduced by granting parents an additional vote for each for their children below the official voting age. Previous research has taken the aging of the voting age population as a given. However, as the work by Sergei and Warren (2007) accurately demonstrates, it is not biological age that determines the specific attitude of the electorate towards pension reforms; the relevant variable to consider is, in fact, the demographic structure of a specific characteristic (e.g., waiting time before retirement age). The demographic structure of such characteristics, unlike the biological age, will be determined by specific pension reforms and will therefore produce a better understanding of how various policies might improve the sustainability of our transfer systems.

Based on the characteristic approach to measuring population aging (Sanderson & Scherbov 2013, this volume), Sergei and Warren (2014, this volume) introduced a normal pension age that increases automatically over time depending on mortality rates. As the authors convincingly argue in their paper, any pension reform that relies on adjusting the pension age needs to be simple to understand, transparent, and intergenerationally equitable. On the basis that the contributions made by each cohort during their working life are equal to the benefits they receive in old age, Sergei and Warren (2014, this volume) obtain a simple formula that relates the ratio of the number of person-years lived prior to the pension age to the number of person-years lived on pension income. This ratio is shown to depend on the replacement rate of pension benefits and the pension tax. Assuming that the replacement rate and the pension tax are fixed across cohorts, improvements in survival will therefore require an increase in the retirement age. Such an approach can be regarded as a demographic indexation of the retirement age based on changes in the lifetable column of the number of years left to live. As convincingly argued in their paper, one of the main advantages of such an adjustment of the pension age may be that it is easy to understand and based on readily available information.

While the first two papers in this section refer to aging populations, the third and fourth deal with the problem of population development as it interlinks with the local environment in developing countries.

Together with his co-authors (Lutz et al. 2002) Sergei developed a simulation model that allows the link between population change, environment, socioeconomic development, and agriculture to be studied. Within this framework, the vicious circle of population growth, poverty, food insecurity, and land degradation can be studied. Central to the vicious circle is the fact that agricultural output is distributed unequally among the population. Those receiving an amount of food that falls below the minimum per capita calorie requirement are defined as food-insecure. Simulations for Ethiopia indicate that it is the rural, illiterate, and food-insecure populations that are inducing increasing land degradation, dependent as they are on the local environment to sustain their livelihoods. Lutz et al. (2004), in their simulation scenarios, also studied the HIV epidemic (which affects mortality and morbidity development) in terms of the future development of Ethiopia. One of the main building blocks of the PEDA model is the multistate population module that distinguishes the population by place of residence, education, and food-security status, in addition to age and sex. The PEDA model demonstrates nicely how the tools of multistate population models and projections can be integrated into models of the interlinkages between socioeconomic development and the environment. To enable a more detailed appreciation of the role of the food distribution mechanism on land degradation and slow economic development, Lutz et al. (2004) developed a reduced-form PEDA model that concentrates on two population groups only: the food-secure and the food-insecure, Compared to the original PEDA model, the reduced-form version provides analytical results and thus insights into the complex nonlinear dynamics inherent in the original PEDA model. However, as argued in their paper, a reduced-form model can never replace a full model that aims to quantitatively replicate the actual time paths.

The papers summarized in this section show how innovative demographic methodologies (like the characteristic approach to the measurement of population aging and multistate population projections) can be applied to gain insight into important societal problems. Sergei has impressively demonstrated how demographic structures that go beyond the simple age and sex schedules can enrich our understanding of development processes. His continuous efforts to highlight the importance of considering the age of individuals not as a static characteristic, but as a property that depends on the demographic and socioeconomic environment, have been rewarded. Sergei is continually invited to give high-level, policy-relevant keynotes and guest lectures and has obtained various prestigious research grants. We need more researchers like Sergei, able to apply their methodological developments to shed light on important societal developments. It is Sergei's strong mathematical background combined with his truly outstanding skills in statistics and numerical simulations that have allowed him to follow this pathway. I am looking forward to many more research papers from Sergei showing us how the tools of demography can improve our understanding of sustainable future development. Happy birthday and many thanks to Sergei for conveying such enthusiasm about formal demography to so many of us in recent years and for the great collaborations we have with him.

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A Near Electoral Majority of Pensioners: Prospects and Policies[1]

Warren C. Sanderson and Sergei Scherbov

Evidence from a variety of sources indicates that the age structure of a population influences the allocation of public spending. Countries with older populations generally spend more on social programs, particularly on those that help the elderly. McDonald and Budge (2005), using data from 21 democracies, found that the proportion of the population aged 65 and older had a strong positive influence on government social spending in the 1990s after controlling for the ideology of the political party in power.

Disney (2007), using data from 21 OECD countries from the 1970s through the 1990s, showed that the size of the welfare state was positively related to the relative size of the population 65 and older. He did not control for political factors, but did control for economic factors that could have had an effect on the size of the welfare state. MacManus (1995) found suggestions in US public opinion poll data that older generations would increasingly push for greater government spending, especially on programs helping them. Poterba (1998) showed that educational expenditures per child decreased significantly in the United States as the proportion of the elderly in school districts increased. Preston (1984), using data from the United States, was one of the earliest to demonstrate the relationship between age structure changes and the allocation of public funds to programs affecting the young and the elderly.

The aging of voting age populations does not imply that voters will shift their party preferences. Rather, as shown in McDonald and Budge (2005), the allocation of public spending depends both on the ideology of the political parties in power and on the age structure. In the long run, political parties, in their competition for votes, respond to the concerns of the electorate. Aging is now rapidly changing those concerns. A good example is the recent legislation in the United States that provides a prescription drug benefit to people 65 and older. This legislation was proposed by a Republican president and passed by two houses of Congress, both controlled by Republicans, even though the Republican Party has traditionally favored less public spending on social programs.

In the first half of the twenty-first century in many of today's more developed countries, the proportion of voting age populations aged 65 and older will roughly double. As voting age populations age, the proportion of net contributors to national budgets (mainly through taxes) will fall and the proportion of net beneficiaries (mainly through pension and health care benefits) will rise. Even ignoring health care expenditures, an unprecedented situation could arise in many countries in which the number of voters receiving net monetary contributions from the government would be close to or outnumber the number of voters making net monetary contributions to it. This is political *terra incognita*.

In this note, we take three steps toward understanding the demography of this new political environment. We do this by considering the cases of Germany, Japan, and the United States. These three countries span almost the entire range of aging experiences to be expected in the coming decades in today's industrialized countries. In the next section we

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investigate the effects of changes in normal pension ages[2] on the proportions of voting age populations receiving public pensions and on the waiting time from the median age of that population to the receipt of a public pension. We show that intergenerationally equitable increases in pension ages could reduce the proportions of voting age populations receiving public pensions in Germany, Japan, and the United States by 10-20 percent. Even in the case of an intergenerationally equitable increase in the pension age, around 40 percent of Japan's voting age population would be receiving a public pension in 2050. Without such an increase in pension age, the corresponding figure would be around 46 percent. Of course, public pensions are not the only source of support for retired people. Private pensions and other forms of savings are also important.

We focus here on public pensions because voting behavior can influence them more directly than other sources of old-age support. In some European countries new public pension arrangements have been introduced, called notional defined contribution plans, that mimic some aspects of fully funded accounts (Holzmann & Palmer 2006). Typically, these plans retain the pay-as-you-go aspect of the financing of public pensions while providing benefits according to schedules that are more akin to those found in fully funded accounts. Regardless of which type of account we are considering, the problem of having a large proportion of the electorate receiving a public pension remains, because voters can always change the parameters of any public pension system.

There are, of course, two ways of reducing the proportion of the voting age population who are receiving a public pension or are close to receiving one. We first consider increases in the normal age for the receipt of a public pension. We then investigate the effects of lowering the voting age. We do this by examining an extreme voting age reform, one that allows parents to vote in place of their not-yet-enfranchised children. This reform has been widely discussed in Germany's political debate and has been formally discussed in the German parliament (Deutscher Bundestag 2004). We analyze it here not because it is politically feasible, but because the calculations provide an illustrative upper bound on the effects of voting age reform.

Large proportions of voting age populations in developed countries in the future will either be receiving public pensions or be expecting to receive one within the next few years. In view of this, it is of interest to ask about the remaining years of life expectancy of future voters. If life expectancy shortens as voting age populations age, voters may be less concerned with the long-run viability of their public pension systems. We show that the life expectancy of median-aged members of the voting age populations of Germany, Japan, and the United States will change only modestly from 2000 to 2050.

The effects of pension age reforms

In Germany, Japan, and the United States, as in many other developed countries, either normal pension ages are already increasing (U.S. Social Security Administration 2004) or legislation is in place (Foreign Press Center Japan n.d.; Sakamoto 2005; U.S. Social Security Administration 2007) to increase them in the future.[3]

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[2] Normal pension age refers to the statutory age at which a full pension would normally be received. It is not the age at which an early reduced pension could be received, the age at which a disability pension could be received, the age at which a bereavement pension could be received, or the age at which any other special category of pensions could be received.

[3] In March 2007 the German Bundestag passed legislation increasing the normal pension age gradually from age 65 to age 67 over a period of 18 years beginning in 2012. During the first

In a standard public pension system that is fully indexed to inflation, it is possible to establish bounds on intergenerationally equitable changes in the public pension age when life expectancies increase. At one extreme is the no-reform option (Option 1), where the normal pension age remains as it was in 2000. This option is not intergenerationally equitable because members of each successive generation contribute the same proportion of their incomes during their working years and receive, on average, ever longer benefit streams as their life expectancies increase. At the other extreme, we consider an increase in the normal pension age such that the average number of years of pension receipt remains fixed and all increases in life expectancy lengthen the time before a pension can be received (Option 3). Option 3 is also not intergenerationally equitable. Successive generations pay ever more into the pension systems because of increases in life expectancies, only to receive benefits over a period that is on average of constant length.

Intergenerationally equitable changes in the normal public pension age must fall between Option 1 and Option 3. In Option 2, the normal pension age is taken as the average of the ages in Options 1 and 3, and the option provides us with an estimate of an intergenerationally equitable change in pension age. In Option 2, workers finance a portion of their additional years of pension with additional years of pension contribution. Option 2 corresponds roughly to an increase in the pension age by one month per year, Option 3 to an increase in the pension age by two months per year (Sanderson & Scherbov 2005).

The current voting age in Germany and the United States is 18. In Japan, it is 20. In our calculations, we assume that these ages do not change. Normal pension ages in 2000 are assumed to be 65 years in all three countries.

The population forecasts used here are a deterministic version of the probabilistic forecasts in Sanderson and Scherbov (2005) using the mean scenario. Values of the total fertility rate and life expectancy at birth (both sexes) are as follows:

	Germany		Japan		United States	
Year	TFR	e_0	TFR	e_0	TFR	e_0
2000	1.4	77.7	1.4	81.1	2.1	76.9
2025	1.4	82.8	1.4	86.2	2.0	81.8
2050	1.5	87.9	1.5	91.3	1.9	86.9

Table 1 shows the percentages of voting age populations at or above the normal pension ages for each of the three options. By 2050, adopting Option 2 causes the percentage of people of pension age in the voting age population to fall by 7 percentage points in Germany, from 39 (under Option 1) to 32 percent, by 6 percentage points in Japan, from

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12 years, the normal pension age is to increase by one month per year. During the next six years, it is to increase by two months per year. Japan has a two-tiered pension system, with a national pension covering everyone in the country and a separate tier based on a person’s type of employment. The normal pension age in the national system is Reforms in 2004 stipulate that the normal pension age for an employee’s pension is to rise gradually from 60 to 65 by 2025 for men and by 2030 for women. In the United States, normal pension ages are currently increasing. The normal pension age was 65 for those born up to 1938. It then began increasing by two months per year, a process what will come to a temporary halt with the cohort born in 1943, when the normal pension age will be The normal pension age will increase again at the rate of two months per year beginning with those born in 1956 and will stop with those born in 1960 at a constant normal pension age of 67. According to the German pension age reform, people born in 1964 and thereafter would have a constant pension age of 67.

46 to 40 percent, and by 5 percentage points in the United States, from 29 to 24 percent. Note, however, that even with this pension age reform, the percentage of the voting age population at or above the normal pension age in Japan almost doubles from 2000 to 2050.

Table 2 provides a different perspective on the effects of pension age reform. By 2050, without further changes in the normal pension age, a majority of the Japanese voting age population would be either receiving a pension or within 2.4 years of doing so, assuming that no one receives an early public pension for disability or other reasons. Allowing for early pensions, it is clear that more than half of Japan's voting age population could be net beneficiaries of government expenditures some time around mid-century. Under Option 2, a majority of the Japanese voting age population in 2050 will be either above the normal pension age or within 6.9 years of receiving a public pension, again not allowing for any early pension recipients.

Without further increases in the normal pension age, a majority of the German voting age population in 2050 would be either receiving a public pension or within 7.3 years of receiving one, again not taking early pensions into account. Early pensions have been popular in Germany and if they are not curtailed, Germany could, like Japan, have a majority of its voting age population as net beneficiaries of government expenditures around mid-century. Assuming Option 2, a majority of the German voting age population would either be above the normal pension age or within 12.5 years of it.

The normal pension age is already increasing in the United States roughly in line with Option 2, although additional legislation would be needed to continue the pension age increases in the future. In 2000, a majority of the US voting age population was above the normal pension age or within 21.7 years of it. Under Option 2, that would change only marginally. The interaction between aging and politics is likely to be much less of a problem in the United States than in other developed democracies. This is consistent with Bergstrom and Hartman's (2005) demonstration of the political feasibility in the United States of a policy of increasing the normal pension age by one-eighth of a year per calendar year. This implied path of normal pension ages would be roughly halfway between our Options 2 and 3.

Pension age reforms, while useful for the sustainability of pension systems, will not, by themselves, prevent significant increases in the proportion of voting age populations who

Table 1. Percentage of voting age population at or above the normal pension age under three options, (1) no change in normal pension age, normal pension age increases one month per year, and (3) normal pension age increases two months per year: Germany, Japan, and the United States 2000-50

	Germany			Japan			United States		
Year	Opt. 1	Opt. 2	Opt. 3	Opt. 1	Opt. 2	Opt. 3	Opt. 1	Opt. 2	Opt. 3
2000	20.1	20.1	20.1	21.7	21.7	21.7	16.6	16.6	16.6
2010	24.4	23.3	22.1	27.5	26.3	25.0	16.9	16.2	15.4
2020	26.7	24.1	21.6	34.1	31.9	29.5	20.9	18.9	17.0
2030	32.8	27.8	23.2	36.6	33.0	29.7	25.7	22.7	19.8
2040	37.0	32.4	26.8	42.2	36.1	30.4	27.4	24.0	20.5
2050	38.6	32.3	26.4	46.4	40.2	33.6	28.5	23.9	19.5

Note: See text for further discussion of options.

Source: Figures are computed from the mean scenario in Sanderson and Scherbov (2005).

Table 2. Waiting time (in years) from median age of voting age population to normal pension age under three options, (1) no change in normal pension age, (2) normal pension age increases one month per year, and (3) normal pension age increases two months per year: Germany, Japan, and the United States 2000-50

	Germany			Japan			United States		
Year	Opt. 1	Opt. 2	Opt. 3	Opt. 1	Opt. 2	Opt. 3	Opt. 1	Opt. 2	Opt. 3
2000	18.8	20.5	22.6	15.8	17.2	18.8	21.7	23.3	25.1
2010	16.2	18.7	21.6	13.2	15.1	17.4	19.4	21.6	24.1
2020	12.5	15.5	19.1	10.8	13.4	16.4	18.0	20.8	24.1
2030	10.2	13.9	18.4	7.8	11.0	14.8	16.9	20.4	24.6
2040	8.9	13.4	18.9	4.5	8.3	12.8	15.6	19.8	24.8
2050	7.3	12.5	18.9	2.4	6.9	12.3	14.5	19.4	25.3

Note: See text for further discussion of options.

Source: Figures are computed from the mean scenario in Sanderson and Scherbov (2005).

are net beneficiaries of government expenditures, especially in countries like Germany and Japan. Pension reforms, which do not include raising the normal pension age, can also be useful in maintaining the stability of pension systems, but they do not address the political problem of electoral majorities voting on their own pension levels.

Voting age reform: Demeny voting

In addition to increasing the normal pension age, proportions of voting age populations receiving or being close to receiving a public pension can be reduced by lowering the voting age. There are many possible reforms of voting age regulations. Here we consider a radical proposal, giving parents the right to vote as proxies for their children who are too young to vote themselves. We call this "Demeny voting," after Paul Demeny who suggested it (Demeny 1986). Demeny voting has recently been under active discussion in Germany (Deutscher Bundestag 2004; Weimann 2002). It is of interest to us here primarily because it is an extreme case of voting age reform. Politically feasible forms of voting age reform will have much less impact.

Demeny voting requires that we redefine the voting age population as the population at or above the legal minimum age for voting weighted by the factor one plus the number of children in each person's custody. For simplicity, we can think of women voting for all their underage female children and men for their underage male children.

As can be seen from Table 3, Demeny voting in Germany with no future changes in the normal pension age would result in the proportion of the Demeny voting age population at or above the normal pension age in 2050 of 33.1 percent. In the absence of Demeny voting, the proportion of the voting age population in that age group would be 38.6 percent (see Table 1). In 2000 (without Demeny voting), the proportion was 20.1 percent. For such an extreme voting age reform, the change in the proportion at or above the normal pension age of only 5.5 percentage points may seem small: it reflects the prevailing low fertility, hence the low proportion of the population below the normal voting age. Indeed, more modest reforms would have even more modest results.

Demeny voting in Germany combined with Option 2 with respect to the pension age reform would result in the percentage of the Demeny voting age population at or above the normal pension age rising to around 28 percent by 2040 and then stabilizing. This

Table 3. Percentage of voting age population above normal pension age in 2000, and percentage of total population above normal pension age with Demeny voting under three options, (1) no change in normal pension age, (2) normal pension age increasesone month per year, and (3) normal pension age increases two months per year: Germany, Japan, and the United States 2010-50

	Percentage of voting age population above normal pension age		
Year	Germany	Japan	United States
2000	20.1	21.7	16.6

	Percentage of total population above normal pension age with Demeny voting								
	Germany			Japan			United States		
	Opt. 1	Opt. 2	Opt. 3	Opt. 1	Opt. 2	Opt. 3	Opt. 1	Opt. 2	Opt. 3
2010	20.4	19.5	18.5	22.4	21.4	20.4	12.8	12.2	11.7
2020	22.6	20.4	18.2	28.4	26.5	24.5	16.1	14.5	13.1
2030	27.8	23.6	19.7	31.1	28.1	25.2	20.0	17.6	15.4
2040	31.7	27.8	23.0	36.0	30.8	26.0	21.5	18.9	16.1
2050	33.1	27.7	22.7	39.8	34.5	28.9	22.6	18.9	15.4

Notes: Figures for 2000 do not take Demeny voting into account. Calculation treats the total population as if it were the Demeny voting age population. This is a close approximation, but it does produce a slight downward bias in the percent- ages, especially for Japan under Option 1. This is consistent with our interpretation of the Demeny voting results as showing the maximum possible effect of a voting age reform. See text for further discussion of options.

Source: Figures are computed from the mean scenario in Sanderson and Scherbov (2005).

combination of policies could simultaneously serve a number of purposes. The increase in the normal pension age would help make the pension system sustainable and decrease the proportion of possible votes cast by those at or above the normal pension age. Further, Demeny voting could be one among a set of policies aimed at supporting higher fertility. (Feedback arising from this source is not taken into account in our calculations on the effects of voting reform: they reflect only the TFR assumptions specified in the text table on page 546.)

The situation in Japan is similar. Adding Demeny voting to Option 2 would reduce the percentage at or above the normal pension age in 2050 from 40.2 to 34.5 percent. Without both changes it would be 46.4 percent. Changing the normal pension age by about one month per year has roughly the same effect on the percent of the voting age population at or above the normal pension age in 2050 as allowing parents to vote for all their not-yet-enfranchised children.

In the United States, increases in the normal pension age already being applied roughly follow Option 2 through 2027. If the United States continues on that path, around 23.9 percent of the voting age population will be at or above the normal pension age in 2050, up from 17 percent in 2000. If Demeny voting is added to the mix, the percentage rises only to 18.9 percent at mid-century.

More politically feasible voting age reforms, such as reducing voting ages by two years, would have only marginal effects on the proportions of the voting age population above or near the normal pension age. Indeed, even with Demeny voting, without further reforms in the age of pension receipt, the proportion of Japan's voting age population receiving a public pension would increase by around 65 percent between 2000 and 2050.

Median life expectancies of voting age populations

The life expectancies of voters could influence how they evaluate the desirability of policies with long-run payoffs compared with those having short-term payoffs. In an era of increasing life expectancies, people of any particular age in the future will have longer remaining life expectancies than people of the same age today. The change in life expectancy of the median-aged person in the voting age population depends on how fast the median age changes over time compared with how fast remaining life expectancy increases.

Of course, most people do not know their life expectancies; nevertheless, they plan for their future. In doing so, they get information from a wide variety of sources including financial advisors, their doctors, the media, and their own observations. On average, all of these inputs would lead adults of any given age to make their plans about the future on the basis of longer time horizons than people of the same age a generation earlier. Evidence shows that the subjective probabilities of survival used in making those future plans are consistent with life table probabilities when they are aggregated by age (Hurd & McGarry 1995), (2) change as predicted with new health information (Hurd & McGarry 2002), and (3) are associated as expected with patterns of saving and consumption (Salm 2006).

In order to provide an indicator of life expectancy that can be compared with a population's median age, Table 4 shows the age of an individual in the year 2000 who has the same remaining life expectancy as a person at the median age of the voting age populations of Germany, Japan, and the United States in the years 2010-50. This type of age measure was first introduced in Sanderson and Scherbov (2005) and is robust to whether it is measured using period or cohort life tables (Sanderson & Scherbov 2007).

We forecast the median age of a member of Germany's voting age population in 2050 to be around 58. Because of increases in life expectancy, he or she will have the same life expectancy as a 48-year-old German in 2000. Since the median-aged member of Germany's voting age population was 46 years in 2000, the life expectancy of Germany's median-aged voting age population member will barely budge during the first half of the century. Most of the increase in the median age of Germany's voting age population is likely to be offset by an increase in life expectancy.

Japan's voting age population will age faster than Germany's, but still increases in life expectancy are expected to offset the better part of the in- crease in the median age of the country's voting age population. The voting age population in the United States will age more slowly, and life expectancy increase will probably outpace it. An individual at the median age of the US voting age population in 2050 will have the same life expectancy as a 42-year-old in 2000, which is slightly less than the observed median age of the voting age population in that year. Generally speaking, because life expectancy increases in most developed countries are likely to be similar in magnitude to anticipated increases in the median ages of voting age populations, life expectancies at those median ages are not forecasted to change much during the period up to 2050. To the extent that interest in policies with longer-term payoffs is influenced by those life expectancies, we would not expect the interest in those policies to change much either. In particular, even with large increases in proportions of voting age populations receiving or being close to receiving a public pension, we would not expect interest in a sustainable public pension system to diminish.

Table 4. Median age of voting age population and age of a person in 2000 who would have the same life expectancy as a person at the median age in the specified year: Germany, Japan, and United States, ten-year intervals 2000-50

	Germany		Japan		United States	
Year	Median age of voting age population	Age of a person in 2000 who would have the same life expectancy as a person at the median age of the voting age population	Median age of voting age population	Age of a person in 2000 who would have the same life expectancy as a person at the median age of the voting age population	Median age of voting age population	Age of a person in 2000 who would have the same life expectancy as a person at the median age of the voting age population
2000	46.2	46.2	49.2	49.2	43.3	43.3
2010	48.8	46.8	51.8	49.9	45.6	44.0
2020	52.5	48.6	54.2	50.5	47.1	43.7
2025	54.2	49.3	55.5	51.0	47.5	43.2
2030	54.9	49.0	57.2	51.8	48.1	43.0
2040	56.1	48.5	60.5	53.5	49.2	42.6
2050	57.7	48.2	62.6	53.7	50.5	41.7

Note: All figures are for both sexes combined.

Source: Figures are median values computed over 1,000 probabilistic forecasts. See Sanderson and Scherbov (2005) and Lutz, Sanderson, and Scherbov (2001).

Discussion

The voting age population and the voting population are not the same. They differ for two main reasons. First, age-specific voting participation rates differ. Typically, younger people vote less often than older people. Second, some people in the population are not citizens and therefore not eligible to vote. In the United States, the median age of voters in the 2004 presidential election was about 3.5 years older than the median age of the voting age population (U.S. Census Bureau 2006). In national elections around 2000 in Japan, the difference was similar (AARP Global Aging Program n.d.). In Germany the difference was about two years (Statistisches Bundesamt Deutschland 2003). It is not clear whether these differences will persist or how they might change. If the median age of Japanese voters remained around 3.5 years higher than the median age of the voting age population, then the median age of Japanese voters in 2050 would be close to 65. In the short run, at least, we would expect that the median voter would remain a few years older than the median member of the voting age population.

We do not think that it is in the interest of pensioners to block all public pension reforms. Pensioners and the young are natural allies on the issue of raising the normal pension age. Pensioners have an interest in raising the pension age for others, because it leaves more money available for themselves and because it lowers pressure to reduce their benefits. Raising the normal pension age would mean lower taxes for the working-age population. This is also in the interest of pensioners, with their long life expectancies, because it is not in their interest to raise taxes on workers to unsustainable levels. Therefore, in some countries it might be easier to pass pension age reform when the voting age population is much older than it is now rather than in the near term when a substantial fraction of the voting age population would be looking forward to soon receiving a public pension. Still, by that time, it might be rather late for pension age reform to help maintain the sustainability of the pension system itself.

As we move toward mid-century, we will be entering new political terrain. Without further reforms, some wealthier countries are likely to have a majority or near majority of their electorates receiving public pensions by 2050. Crucial steps to reduce potential future problems could be much easier to take now than they will be in a few decades (Sinn & Uebelmesser 2003; Uebelmesser 2004). Demographic analysis has an important role to play here both by showing what our future is likely to be in the absence of additional reforms and by quantifying the effects of our policy options.

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An Easily Understood and Intergenerationally Equitable Normal Pension Age[1]

Warren C. Sanderson and Sergei Scherbov

1 Introduction

In public policy, age matters. A myriad of policies stipulate rights, obligations, benefits, and taxes on the basis of chronological age. Chronological age is a simple, easily understood characteristic of people and this makes it particularly useful in the specification of public policies. Nevertheless, several different factors now converge suggesting that, at least with respect to some policies, the treatment of age needs to be rethought, particularly in view of changes in longevity. On a theoretical level, Sanderson and Scherbov (2013) argue that ageing is a multidimensional phenomenon and that it needs to be studied on the basis of the characteristics of people. Chronological age is one characteristic of people, but for specific public policies it might not necessarily be the most relevant one, especially because it does not vary with longevity. On a general policy level, Shoven (2007) and Shoven and Goda (2010) show that the US public policies concerning the normal pension age, the age at eligibility for Medicare (health insurance for the elderly), and ages in tax-advantaged savings plans, would be quite different if those ages were indexed for changes in longevity. On the level of policy implementation, public pension programs are in the process of change in most OECD countries (OECD 2013). Those changes frequently involve changes in normal pension ages.

In the provision of public pensions, fixed normal pension ages are already being replaced by variable ones. The conceptual basis for those variable normal pension ages, however, often remains unexplored and unarticulated. The purpose of this paper is to provide a clearly defined and analytically-based model of normal pension ages. Our approach produces hypothetical normal pension ages that are simple to understand, transparent, intergenerationally equitable, and vary with changing mortality conditions. Model-based normal pension ages are useful because they have known properties. A comparison of country policies with model-based normal pension ages can be useful in assessing those country policies.

Among wealthier countries in recent years one topic has been particularly contentious – changes in pension ages. Pension age changes have been challenged for a number of reasons. Important among these is the evident unfairness of the changes. Governments sometimes make the argument that changes in normal pension ages are needed because pensions are expensive and the government does not have the money to pay them. This argument is certainly unpersuasive. If the government does not have enough money, it can get it in any number of ways. It can reduce subsidies to various firms and sectors of the economy. It can produce its services more efficiently. It can stop performing services that have little or no value or are targeted to those in society who are already well-off. It can also raise the general level of taxes. The argument that pensions are expensive and therefore pension ages should be increased is a bit like making the argument that education is expensive and therefore there should be fewer schools. If governments need money, they should produce a balanced plan to raise some. Certainly, pension age changes can be part

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of those reforms, but, if the only problem is a shortage of money, it is unfair to argue that older people should have their benefits reduced, while farmers, among others, should not.

Changes in national pension ages are also problematic because of intercohort inequalities. Changes in national pension age policies are usually written so that people born in one year can get a full pension at, say, 65, while people born a year later can only get a pension when they are older. If the only problem is a shortage of money and the government was devising a fair plan to raise that money, why should a one day difference in birthdays translate into different levels of pension receipt?

Unanticipated changes in normal pension ages are inequitable. Changes in the normal pension age do not change the incomes of current pensioners. Young people have time to change their labor force and saving behavior to adjust to the changes. People near the previous normal pension age suffer because they have made plans based on that age. Episodic changes in normal pension ages during periods of economic duress are certainly a poor approach to the formulation of pension age policy. In order for people to understand, accept, and voluntarily adjust to changes in national pension ages, two criteria must be met. First, the rationale for pension age policy must be compelling, simple and transparent. Second, the resulting policies must be clearly intergenerationally equitable. Currently, in most high income countries, neither criteria is met. Under these circumstances, it is no surprise that pension age changes are so contentious.

The aims of this paper are: (1) to specify an analytically-based national pension age policy that meets both of those criteria, (2) to compute the resulting hypothetical normal pension ages for selected European countries, and (3) to assess the relationship between forecasts of the hypothetical normal pension ages that we compute and the plans that governments have for their normal pension ages.

The paper has 7 sections. In Section 2, we discuss the characteristics approach to the measurement of population ageing (Sanderson & Scherbov 2013). This methodology can be used to produce hypothetical ages based on the characteristics of people. The characteristics approach provides the basis for understanding how those characteristic-based ages could usefully be applied in public policies. In Section 3, we discuss the contributions of Shoven and Goda (2010). Shoven and Goda have provided the first detailed discussion of the effects of incorporating changes in mortality rates on the ages built into various US government policies, including the normal pension age. In Section 4, we discuss the three key features of a desirable normal pension age policy, simplicity, transparency, and intergenerational equity. In that Section, we also present a highly simplified model of a pension system that points to a new way of determining normal pension ages. Among other things, we show in that Section that increasing normal pension ages on the basis of increases in life expectancies at some fixed chronological age does not meet equity criteria. In Section 5, we provide examples of the new analytically-based normal pension ages. In Section 6, we compare our pension ages to those already planned for the future and discuss what could be done to improve welfare if planned pension ages rise too fast. We provide a concluding discussion in Section 7.

2 The Characteristics Approach to the Measurement of Population Ageing

The characteristics approach to the study of population ageing, developed by Sanderson and Scherbov (2013; 2005; 2010; 2008; 2007b), starts from the assumption that ageing is a multidimensional phenomenon. Chronological age is one characteristic of people, but, depending on exactly what is studied, it might not be the most interesting or informative one. Because ageing is multidimensional, a framework is needed that can consistently integrate a variety of characteristics. The fundamental building block of the characteristics approach is a characteristic schedule. A characteristic schedule relates chronological age to the average level of the characteristic in the population.

In mathematical notation, we express the characteristic schedule as $k = C_r(a)$, where k is the level of the characteristic observed at age a in population r. This relationship can be written in the reverse way, where for any level of the characteristic we can find the associated age. This can be expressed by the equation $a = C_r^{-1}(k)$.

We use the term “alpha age” to refer to a characteristic-based age. Alpha ages, in general, are derived from the equation $\alpha = C_s^{-1}(C_r(a))$, where r and s refer to two different characteristic schedules. For example, r and s can refer to the characteristic schedules of a country in different years. α is the age in characteristic schedule s where people have the same characteristic level as they have at age a in schedule r.

We illustrate how alpha ages are computed in Table 1. The table shows two characteristic schedules, one labeled r and the other labeled s. The two characteristic schedules can refer to, among other things, two countries, two years, two genders, two population subgroups, or some combination of these. In the characteristic schedule r, chronological age is shown in the left column and he corresponding characteristic level in the right column. In characteristic schedule s, the order is reversed and we have put the characteristic level on the left and the chronological age on the right. Which one of the two is put on the right or left is immaterial.

Let us begin with the term $C_r(a)$. In Table 1, $C_r(62) = 43$. In other words, people of age 62 in the characteristic schedule r, have the characteristic level 43. The second step in the computation of alpha age is to find the age in characteristic schedule s where people have the characteristic level 43. In mathematical notation this is just $C_s^{-1}(43)$. We can see from Table 1 that people in characteristic schedule s who have the characteristic level of 43 are 64 years old $(C_s^{-1}(43) = 64)$. So we say that the alpha age of people 62 years old in r is 64, when s is used as a standard of comparison.

One crucial question in the study of normal pension ages is what characteristic to use. This question was recently raised in Shoven and Goda (2010), so we turn to their work next.

Table 1. Hypothetical Example of the Computation of an Alpha-Age.

Characteristic Schedule *r*		**Characteristic Schedule *s***	
Chronological Age	Characteristic Level	Characteristic Level	Chronological Age
60	50	48	62
61	47	46	63
62	***43***	***43***	***64***
63	38	41	65
64	32	35	66

3 The Work of Shoven and Goda

Shoven and Goda (2010), building on the work of Shoven (2007), computed what we call alpha ages associated with three US government policies, Social Security (old age pension program), Medicare (health insurance for the elderly), and Individual Retirement Accounts (tax-advantaged saving plans for retirement). They calculated alpha ages corresponding to 7 different chronological ages used in those programs, including the normal pension age. They used 4 different characteristics, remaining life expectancy, equivalent mortality risk, the ratio of remaining life expectancy to life expectancy at birth, and the ratio of remaining life expectancy to life expectancy at age 20.

Table 2 reproduces the portion of their findings for alpha normal pension ages assuming that the characteristic remains fixed at the level for 65 year olds observed in 1935, the year in which the Social Security (national pension) system was introduced. 65 was the normal pension age in the US from 1935 to 2002.

The alpha normal pension age of 71.0 for women using the characteristic "remaining life expectancy" means that women in 2004 who had the same remaining life expectancy as 65 year old women in 1935 were around 71 years old. Another alpha normal pension age uses the characteristic of the ratio of remaining life expectancy to life expectancy at 20. To compute this alpha age, the ratio of the remaining life expectancy of women 65 years old in 1935 to the remaining life expectancy of 20 year old women in that year has to be calculated. The second step is to find the age in 2004 where the ratio of remaining life expectancy to life expectancy at age 20 was the same as in was for 65 year old women in 1935. That age was 74.8.

In mathematical notation, the alpha normal pension ages in Table 2 come from the expression

$$\alpha = C_{2004}^{-1}\left(C_{1935}(65)\right).$$

While it is natural for economic magnitudes to be adjusted for differences in price levels over time and from place to place, many public policies are based on chronological ages that are not adjusted for changes in longevity. Shoven and Goda show clearly that adjusting the chronological ages built into a number of US government policies for longevity changes would have a substantial impact. Their goal was not to decide which of the 4 characteristics that they studied would be best used for adjusting legislated ages in particular instances. Our goal, however, is to decide which characteristic is the best for calculating alpha normal pension ages. In order to do this, we must first be clear about exactly what we want our alpha normal pension ages to accomplish.

Table 2. Alpha Normal Pension Ages in 2004.

Characteristic	**Male**	**Female**	**Total**
Remaining Life Expectancy	73.0	71.0	73.0
Equivalent Mortality Risk	75.0	71.0	74.0
Ratio of Remaining Life Expectancy to Life Expectancy at Birth	83.0	81.9	81.8
Ratio of Remaining Life Expectancy to Life Expectancy at 20	76.1	74.8	76.0

Note: Alpha ages for the characteristics remaining life expectancy and equivalent mortality risk are rounded by Shoven and Goda. *Source*: Shoven and Goda (2010), Table 4.1, p. 152.

4 Ex-Ante Equitable Normal Pension Ages

Our goal in this Section is to determine simple, transparent, and equitable alpha normal pension ages. An alpha normal pension age is different from a normal pension age based on a fixed chronological age. Alpha normal pension ages vary with differing mortality conditions. Thus, we are not seeking a single alpha normal pension age. Rather our goal is to determine the procedure through which mortality conditions could be used in computing normal pension ages with known desirable features. Different mortality conditions will, in general, produce different alpha normal pension ages.

The features that we want in our alpha normal pension age are: (1) simplicity, (2) transparency, and (3) equity. Of the three, the last requires the most explanation. Here we are not talking about social equity, i.e. equity among population subgroups. For the population as a whole two types of equity can be distinguished, *ex-ante* equity and *ex-post* equity. This is similar to the distinction between *process equality* and *outcome equality*. For people to accept a method for determining normal pension ages, it must be clear that it is *ex-ante* equitable. Of course, like any insurance plan, the method will not result in *ex-post* equality. Some people will die before reaching any plausible normal pension age and therefore could have paid into the pension system and gotten nothing in return.

In order to find a mechanism determining alpha normal pension ages with desirable properties, we will consider a grossly simplified pension system. The enormous simplifications are designed to help us see the essence of the situation more clearly. Our simplified representation begins with a cohort starting at age 20. The adult lifecycle is divided into two phases, a pre-pension phase and a pension phase.

Ex ante equality requires that members of each cohort receive as much money in pension benefits as they contribute to the pension system. Systems in which cohorts receive much more or much less than they put in are not *ex ante* equitable. If the members of one cohort receive much more than they contribute to the system, then people in other cohorts have to pay for this. If the members of one cohort pay into the pension system more than they receive in benefits, people in other cohorts are the beneficiaries.

We express the idea that members of each cohort must receive as much money in pension benefits as they contribute to the pension system as:

$$\tau \cdot y \cdot u = p \cdot v, \tag{1}$$

where u is the number of person-years lived by members of the cohort in the pre-pension phase, τ is the pension tax rate on income, y is average income during the pre-pension years, v is the number of person-years lived by members of the cohort in the pension phase, and p is the average annual pension receipt. The term p can be expressed as P/v , where P is the total amount paid out to pensioners in the cohort. Therefore, p is just the average pension receipt per pensioner. The term y can be expressed as Y/u, where Y is the total income of all people in the pre-pension ages. Therefore, y is just the average income of people in the pre-pension ages.

The equation is written without a discount rate. There are several reasons for doing this. First, payments into a pension fund are like investments in a risk-free insurance policy that pays off in perfectly inflation adjusted money. The real rate of interest on the safest government bonds has been close to zero for decades, so using zero discount rates is not out of line with what we observe. Second, with discounting, we would have to introduce details of the time profile of pension contributions and receipts that go far beyond what could be done in this paper and would distract from the central point here. Third, national pension systems have an important social component. They are designed, in part, to help those who have had bad luck or made bad economic decisions in their youth. When this social component is considered, the motivation for discounting becomes less clear.

The most important reason for not discounting has to do with simplicity. Equation (1) says that each cohort gets as much out of the pension system as they put into it. People can understand this and could support a pension system based on it.

There is a second dimension of equality that has to be taken into account here. People would not consider a pension system equitable if pensioners received more money every year than the incomes of those contributing, net of their pension contributions. Countries make a social choice of the level of pension income relative to the after-(pension)-tax income of pre-pensioners. We express this using the equation

$$p = \beta \cdot y \cdot (1 - \tau) \tag{2}$$

where p is the average pension, y is the average income of people in the pre-pension period, τ is the pension tax rate, and β is the ratio of annual pension income to the income of people in the pre-pension period after adjustment for pension contributions. β is the relative generosity of pension benefits. If society makes a decision to reward one cohort by giving it a high β and penalizes another with a low β, this is clearly not equitable.

Equations (1) and (2) can be combined to yield an expression for the ratio of the number of person-years lived in the pre-pension phase to the number of person-years lived in the pension phase.

$$\frac{u}{v} = \beta \cdot \left(\frac{1}{\tau} - 1\right). \tag{3}$$

Equation (3) is simple, but very powerful. It combines two criteria for *ex ante* equity. The first is that each cohort must receive in pension benefits what it contributes to the pension system. The second is that the balance between pension receipts and the income people have in their pre-pension years net of their pension contributions should be the same across cohorts. In this way pensioners are not allowed to grow ever richer at the expense of those who support them or increasingly impoverished for the benefit of younger generations.

A useful feature of our hypothetical pension system is that the pension contribution rate, τ, is the same across cohorts. In practice, the pension contribution rate is usually fixed across cohorts as a matter of practicality. Having different pension contribution rates for different cohorts in the same year would mean that the pension contribution rates would have to differ by age. People would only agree to pay different pension contribution tax rates if governments could credibly commit to providing greater benefits to those who pay the higher rates, which is rarely the case.

In equation (3) if the generosity of the pension system, β, and the pension contribution rate, τ, are fixed, the ratio of u to v is fixed, independent of the level of income. A fixed ratio of u to v is easy to explain. If the ratio of u to v is fixed, then the ratio $\frac{v}{u+v}$ is also fixed. The latter ratio essentially says that for each cohort, the number of years people receive a pension is a fixed proportion of all the years they live from age 20 onward. A pension system based on this fixed ratio is equitable because the ratio is the same for all cohorts regardless of the mortality conditions that they face.

In the computation of alpha normal pension ages, we do not need to investigate using a variety of different characteristics. Equation (3) requires that we use a particular characteristic to set alpha normal pension ages, the ratio of the number of person-years lived in the pre-pension period to the number of person-years lived in the pension period.

The characteristic, $\frac{u}{v}$, is simple to compute using the T_x column of the life table. $u = T_{20} - T_\alpha$ and $v = T_\alpha$, where α is the alpha normal pension age. In terms of life table notation, then $\frac{u}{v} = \frac{T_{20}}{T_\alpha} - 1$, and this equation can easily be solved for the alpha normal pension age.

In addition to being simple to understand, this characteristic has the advantage of being transparent. Life tables are freely available to anyone. Also, because the characteristic on which alpha normal pension ages are based is public and not computed, manipulated, or contested by various factions, it is a strong foundation around which a consensus can be developed.

In Table 3, we show $\frac{T_{65}}{T_{20}}$ for men and women in selected countries in 2013. It is the inverse of the ratio in the equation for $\frac{u}{v}$. We show it in the table because it is easier to interpret. $\frac{T_{65}}{T_{20}}$ is the fraction of all person-years lived from age 20 onward that are also lived at ages 65+. The median proportion of adult person-years lived at age 65+ is 0.2635 for men and 0.3065 for women. All men in the Western European countries in the Table have values above the median and all men in Eastern European countries have values below the median. The same is true for women, except for Ireland, where the value for women is 0.306, just marginally below the median. If the normal pension age were 65, then $\frac{T_{65}}{T_{20}}$ is the fraction of all adult-person years spent in pension. The low $\frac{T_{65}}{T_{20}}$ ratios in Eastern Europeans countries indicate that if the normal pension age were 65, Eastern Europeans would spend a smaller fraction of their adult person-years with a pension than would Western Europeans. If people in the two groups of countries were to have the same ratio of adult person-years in pension, then the normal pension ages would have to be lower in Eastern Europe.

The data underlying Table 3 in this Section and Tables 4 and 5 in the next Section were created as part of the preparation of the European Demographic Datasheet (2014).

Equation (3) shows that alpha normal pension ages should be set so that $\frac{T_\alpha}{T_{20}}$ is fixed. This is close to Shoven and Goda's characteristic of a fixed proportion of life expectancy at age 20, but it is not the same. Shoven and Goda's characteristic $\frac{e_\alpha}{e_{20}} = \left(\frac{T_\alpha}{T_{20}}\right) \cdot \left(\frac{l_{20}}{l_\alpha}\right)$.

Because life expectancies are increasing and life expectancy is the most well-known and well-understood life table function, it is tempting to use life expectancy changes to change normal pension ages, as Shoven and Goda have done. Sweden, Italy, Poland, and Norway have adopted a notional defined contribution pension system where pension contributions are cumulated in a notional account (OECD 2011). At retirement age, the total is turned into an annuity based on life expectancy. This system fails the principle of equity that states that the total amount of money contributed by a cohort to the pension system should be returned to the cohort in terms of pension benefits. Because each person of pension age gets an actuarially fair return on his contributions, the system takes from each cohort the pension contributions of those who do not survive to the pension age. This money might be returned to each cohort or perhaps it is used to fund the pensions of other cohorts.

Another way of using life expectancy as a basis of changing normal pension age is to increase normal pension ages according to some fraction of the increase in life expectancy at a specific age. There is no guarantee that this procedure would be equitable either. Further, because it is not based on a clear definition of equity, questions would always arise as to what fraction of the increase in life expectancy to use and at what age to measure it.

Alpha normal pension age is a simple, transparent, and equitable normal pension age. It is based on clear assumptions about the features of an equitable pension age. In the next Section, we present those ages for a selected set of European countries.

5 Temporal Paths of Equitable Normal Pension Ages

In Table 4, we show alpha normal pension ages based on the formula $\alpha = C_s^{-1}(C_r(65))$, where $C(a) = \frac{T_{20}}{T_\alpha} - 1$, r refers to a specific combination of country, gender, and the year 2013, and s refers characteristic schedule of various years of interest for that country and gender. Computed in this way, all alpha normal pension ages in 2013 are assumed to be 65.

Table 4 shows that if 65 is the appropriate normal pension age in 2013, then for most countries, in order to keep the proportion of adult person-years in pension constant, the normal pension age should increase to between 69 and 70 by 2050. The similarity in the normal pension ages across countries is more interesting than it first appears. The ratio of adult person years spent at age 65 and beyond to all adult person-years varies across countries in 2013. For men, it was lowest in the Russian Federation, where it was 0.156 and highest in Italy, where it was 0.277. The lowest level for women was also in the Russian Federation, where it was 0.247. The highest level for women was in France, where one-third of all adult person-years was spent at age 65 or beyond. Nearly constant alpha pension ages

Table 3. $\frac{T_{65}}{T_{20}}$ for men and women in selected countries in 2013.

	Males	**Females**
Bulgaria	0.194	0.257
France	0.276	0.333
Georgia	0.198	0.264
Germany	0.264	0.307
Greece	0.263	0.307
Ireland	0.267	0.306
Italy	0.277	0.325
Latvia	0.182	0.269
Russian Federation	0.156	0.247
Serbia	0.202	0.249
Slovakia	0.207	0.274
Spain	0.271	0.325
Sweden	0.275	0.309
United Kingdom	0.271	0.307

Note: $\frac{T_{65}}{T_{20}}$ is the ratio of all person-years lived from age 20 onwards that are also lived after age 65.

Source: Authors calculations based on life tables prepared for the European Demographic Data Sheet (Anon 2014).

across countries over time indicates that the forecasts in the European Demographic Data Sheet (Anon 2014) envision that the countries with low ratios continue to have low ratios and those with high ratios continue to have high ratios. Convergence in the proportion of person-years spent at more advanced ages to all adult person-years is not envisaged.

Table 5 shows the alpha pension ages keeping constant the person-years ratio for Germany in 2013. An interesting policy question is what normal pension ages should be if European countries moved toward a common policy with respect to those pension ages. Table 5 presents a concrete example of that policy based on alpha normal pension ages. The result would be very similar if we took any Western European country in 2013 as the standard. For German women and men the alpha pension age increases to almost 70 by 2050. Alpha pension ages are almost identical for Greece as they are for Germany. France has marginally higher alpha pension ages than the Germans and Greeks. Russians and the people in Eastern European countries have considerably lower alpha normal pension ages. The alpha normal pension age for Russian men in 2013 is only 57.30. Russian women have an alpha pension age of 60.99 in 2013, over 3 years higher than that of men. By 2050, the gap between the alpha pension ages of Russian men and women is forecasted to shrink a bit, but the alpha pension age for Russian men is still only 62.41 in that year.

6 Comparison of Increases in Alpha Normal Pension Ages to Planned Changes

In this section, we compare changes in alpha pension ages with current plans to change normal pension ages using Germany in 2013 as a standard (characteristic schedule *s*). An important policy question is whether countries should strive to have roughly the same normal pension ages in the future. Our approach suggests that they should not try to have similar normal pension ages based on chronological age, but rather that they could try to have similar alpha normal pension ages. Having similar alpha normal pension ages are preferable because they take mortality differences into account. We use Germany in 2013 as our standard to help us look at what converged alpha normal pension ages could look like in the future. Had we used any other Western European country in 2013 as a standard the results would be similar. In Table 5, the alpha pension ages for Germany are a bit over 67 years old for both men and women in 2030. Currently, the normal pension age in Germany is scheduled to increase to 67 by 2029. The alpha normal pension ages and the planned normal pension age match almost exactly. In Spain, the normal pension age is scheduled to rise to 67 in 2027. The alpha pension ages for women and men in 2030 are 67.93 and 67.57 respectively. Again the match between the alpha pension ages and the legislated ones is close. Italian pension reforms call for the normal pension ages of men and women to increase to 66 in 2018. The alpha pension ages for women and men in 2020 are 66.93 and 66.46 respectively. Again the match is close. After 2018, there will be an automatic linkage between the changes in the normal pension age and increases in life expectancy. This is not consistent with the equity criteria that we discussed above.

Some countries have legislated increases in normal pension ages that are faster than those suggested by the alpha normal pension ages. In the UK, normal pension ages are scheduled to rise to 67 by 2026. The alpha pension age for women in 2030 is 66.98 and it is 67.32 for men. The rise in the UK normal pension age is slightly faster than the rise in alpha pension ages. In Ireland, the legislated increase in normal pension age is much faster than the increase in alpha pension ages. The normal pension age is scheduled to increase to 68 in 2028 in Ireland. In 2030, the alpha normal pension ages are 66.88 for men and 66.80 for women. Greece has already increased its normal pension age to 67, while its alpha pension

Table 4a. Alpha normal pension ages for women in selected European countries, 2013, 2020, 2030, 2040 and 2050.

Women					
Country	**2013**	**2020**	**2030**	**2040**	**2050**
Bulgaria	65.00	65.42	66.63	67.83	69.13
France	65.00	65.65	66.88	68.03	69.28
Georgia	65.00	65.37	66.55	67.77	69.04
Germany	65.00	65.82	67.09	68.34	69.62
Greece	65.00	65.97	67.32	68.59	69.88
Ireland	65.00	65.68	66.86	68.07	69.31
Italy	65.00	65.65	66.89	68.13	69.37
Latvia	65.00	65.68	66.88	68.13	69.36
Russian Federation	65.00	65.37	66.46	67.50	68.58
Serbia	65.00	65.63	66.90	68.18	69.49
Slovakia	65.00	65.78	67.04	68.30	69.61
Spain	65.00	65.41	66.63	67.85	69.09
Sweden	65.00	65.70	66.90	68.14	69.40
United Kingdom	65.00	65.68	66.97	68.19	69.41

Note: Alpha normal pension ages are based on the ratio $\frac{T_{20}}{T_{65}}$ observed in the country in 2013.

Source: Authors' Computations based on data compiled for the European Demographic Data Sheet (Anon 2014).

Table 4b. Alpha normal pension ages for men in selected European countries, 2013, 2020, 2030, 2040 and 2050.

Men					
Country	**2013**	**2020**	**2030**	**2040**	**2050**
Bulgaria	65.00	65.60	66.96	68.31	69.69
France	65.00	66.09	67.52	68.74	70.02
Georgia	65.00	66.17	67.54	68.89	70.27
Germany	65.00	66.00	67.45	68.70	69.99
Greece	65.00	66.19	67.58	68.84	70.15
Ireland	65.00	65.56	66.71	67.89	69.10
Italy	65.00	65.57	66.84	68.14	69.40
Latvia	65.00	66.17	67.80	69.39	70.83
Russian Federation	65.00	65.69	67.33	68.81	70.22
Serbia	65.00	65.97	67.27	68.54	69.85
Slovakia	65.00	65.92	67.46	68.85	70.26
Spain	65.00	65.61	67.05	68.35	69.64
Sweden	65.00	65.66	66.87	68.07	69.34
United Kingdom	65.00	65.58	66.82	68.00	69.23

Note: Alpha normal pension ages are based on the ratio $\frac{T_{20}}{T_{65}}$ observed in the country in 2013.

Source: Authors' Computations based on data compiled for the European Demographic Data Sheet (Anon 2014).

age is still around 65. France is an interesting example of a country with a normal pension age much below its alpha normal pension age. In 2050, France is the country in Table 5 with the highest alpha normal pension ages. If its normal pension age remains at 62, France at that time will be massively out of step with much of Western Europe.

Normal pension ages tend to be lower in Eastern European countries, as alpha normal pension ages suggest they should be. Typically, the pension ages for men are higher than for women, which is the opposite of what the alpha normal pension ages suggest they should be. In the Russian Federation, for example, the normal pension age is currently 60 for men and 55 for women. The alpha normal pension ages are 57.30 for men and 60.99 for women. Russian normal pension ages are now very roughly consistent with those in Western Europe, taking life expectancy differences into account.

Alpha normal pension ages are a simple analytic tool for discussing the evolution of normal pension ages. In this section, we showed that they are close enough to the legislated paths to make interesting comparisons. Alpha normal pension ages are easy to understand, easy to compute, and provide informative comparisons to legislated values.

7 Concluding Discussion

In Table 5, alpha normal pension ages rise to 70 for many countries by 2050. Alpha normal pension ages are designed to be fair, but it is sometimes argued that substantial increases in normal pension ages make the pension system more unfair. People in physically hazardous or especially arduous occupations might not be physically capable of working to age 70. It is certainly true that some people may not be able to work to age 70, but this does not automatically mean that normal pension ages should not be raised. Alpha pension ages are fair pension ages. Keeping pension ages fixed is unfair.

Alpha pension ages rise over time because of increases in the remaining life expectancy of older people and higher survivorship to older ages. In the past increased life expectancy has been associated with better health at older ages and better cognitive functioning (Vaupel 2010; Christensen et al. 2009; Baudisch & Vaupel 2012; Weber et al. 2014; Bordone et al. 2014). When people picture whether people can or cannot work up to age 70, they naturally picture today's 70 year olds. But tomorrow's 70 year olds will be different. They will be healthier, better educated, and it is likely that they would more attracted to market work than today's 70 year olds (Scherbov, Sanderson, KC, et al. 2014).

Nevertheless, it would be unwise to ignore the distributional effects of increasing normal pension ages. In Economics, there is a rule of thumb that states that policy-makers should have at least policy available to them for every target that they wish to attain. The single policy, changes in normal pension ages, should not be treated as being capable of simultaneously hitting the two policy targets. This is why in many countries, pension reforms that increased normal pension ages also provided additional support to people who had difficulties continuing to work at older ages (OECD 2014).

In some cases, such as that of Ireland, planned increases normal pension ages are considerably faster than those in alpha normal pension ages. Reducing the speed of the planned increases, in these cases, could make the pension system more intergenerationally equitable. It would, however, increase government expenditures. It could be possible for governments to add to their revenues by reducing labor market distortions which discourage people who would otherwise wish to work. In (Scherbov, Sanderson & Mamolo 2014) we showed that, in many European countries, a one to two percentage point increase in the average labor force participation rates resulting from a decrease in labor market distortions

Table 5a. Alpha normal pension ages for women in selected European countries, 2013, 2020, 2030, 2040 and 2050.

Women					
Country	**2013**	**2020**	**2030**	**2040**	**2050**
Bulgaria	61.70	62.09	63.26	64.43	65.67
France	66.90	67.57	68.82	70.01	71.29
Georgia	62.17	62.53	63.67	64.85	66.06
Germany	65.00	65.82	67.09	68.34	69.62
Greece	64.98	65.95	67.30	68.57	69.86
Ireland	64.94	65.62	66.80	68.00	69.24
Italy	66.28	66.93	68.20	69.47	70.73
Latvia	62.49	63.15	64.31	65.52	66.72
Russian Federation	60.99	61.34	62.41	63.41	64.46
Serbia	61.21	61.81	63.02	64.25	65.50
Slovakia	62.81	63.58	64.81	66.03	67.29
Spain	66.29	66.70	67.93	69.18	70.45
Sweden	65.13	65.83	67.03	68.27	69.54
United Kingdom	64.99	65.67	66.96	68.18	69.40

Note: Alpha normal pension ages are based on the ratio $\frac{T_{20}}{T_{65}}$ observed in Germany in 2013.

Source: Authors' Computations based on data compiled for the European Demographic Data Sheet (Anon 2014).

Table 5b. Alpha normal pension ages for men in selected European countries, 2013, 2020, 2030, 2040 and 2050

Men					
Country	**2013**	**2020**	**2030**	**2040**	**2050**
Bulgaria	60.25	60.82	62.14	63.44	64.78
France	65.83	66.92	68.36	69.59	70.87
Georgia	60.52	61.64	62.97	64.28	65.61
Germany	65.00	66.00	67.45	68.70	69.99
Greece	64.91	66.09	67.48	68.74	70.05
Ireland	65.18	65.73	66.88	68.07	69.29
Italy	65.89	66.46	67.74	69.05	70.33
Latvia	59.34	60.46	62.03	63.57	64.97
Russian Federation	57.30	57.96	59.56	61.00	62.41
Serbia	60.86	61.80	63.07	64.31	65.59
Slovakia	61.15	62.04	63.53	64.89	66.27
Spain	65.52	66.12	67.57	68.87	70.17
Sweden	65.75	66.41	67.63	68.85	70.11
United Kingdom	65.49	66.06	67.32	68.50	69.74

Note: Alpha normal pension ages are based on the ratio $\frac{T_{20}}{T_{65}}$ observed in Germany in 2013.

Source: Authors' Computations based on data compiled for the European Demographic Data Sheet (Anon 2014).

could compensate for a one year decrease in the normal pension age in terms of the burden of workers supporting those not in the labor force. A joint policy change, simultaneously reducing labor market distortions and reducing the speed of increase in the normal pension age, could result in a more equitable pension system without a loss of revenue to the government. It would be a win-win policy because labor markets would be less distorted and the pension system would be more equitable.

Two different approaches to changing normal pension ages has emerged in Europe. One is to set targets for normal pension ages, often a decade or more in the future. After a while a new set of political negotiations is necessary to produce new targets. This episodic policy making has an important problem. As countries age, it is likely to become ever more difficult politically to make the needed reforms of normal pension ages. In Sanderson and Scherbov (2007a), we showed that by 2050 around 39 percent of Germany's voting age population would be 65+ years old.

The alternative approach increases normal pension ages continuously as life expectancy increases. This approach is currently implemented in Sweden and will be implemented in Italy from 2018 onward. This form of demographic indexation is a step in the right direction, but indexation based on the T_x column of the life table rather than the e_x column would be preferable. Alpha pension ages provide a helpful guide to continuous modification of pension ages because those ages are based on an easily understood principle that is readily seen as fair. Policy-makers should consider replacing episodic changes in normal pension ages with continuous ones based on alpha normal pension ages.

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Population, Natural Resources, and Food Security: Lessons from Comparing Full and Reduced-Form Models[1]

Wolfgang Lutz, Sergei Scherbov, Alexia Prskawetz, Maria Dworak and Gustav Feichtinger

Any analysis of the complex interactions between human population dynamics and the natural environment requires some sort of model, either in one's mind or on paper or on the computer. If the objective is to come up with quantitative estimates of future trends and interactions, explicit mathematical (and mostly computer-based) models are the appropriate tool. Since there are myriads of possible models determined by the choice of variables and parameters, the level of aggregation, and the complexity of the model, the scientist entering this field will have to make a daunting number of choices for which he/she often has little scientific basis. While the choice of variables and the level of regional aggregation tend to be strongly influenced by the specific research question, the issue of model complexity is more ambiguous. Are complex models more or less appropriate than simple ones? This general question has been addressed in different contexts (see, e.g., in the field of population forecasting Rogers 1995a; Lee et al. 1995; Sanderson 1999) . Here we want to study the question in the context of dynamic population-environment modeling by comparing a recently developed large empirical model to its reduced-form derivative.

This chapter is built around an interactive simulation model, the PEDA (population, environment, development, agriculture) model, which focuses on the interactions between changes in population size and distribution, natural resource degradation, agricultural production, and food security (Lutz & Scherbov 2000). This recently developed model has been inspired by the “vicious circle” reasoning (Dasgupta 1993; Nerlove 1991), which assumes a dynamic relationship between resource degradation, poverty (food insecurity), and high fertility. PEDA explicitly includes these variables, which are necessary to model the “vicious circle,” but it is not limited to its specific assumptions. PEDA is a much more general tool, which can calculate the longer-term implications of a great range of alternative assumptions. It is also used for science-policy communication. The major message to be conveyed to policymakers is that population, education, rural development, land degradation, water, food production, and food distribution are not independent issues (usually addressed independently by different ministries), but rather these trends are interconnected in the real world and need to be addressed in a way that takes account of this nexus. PEDA is being coordinated by the UN Economic Commission for Africa and has been applied to a number of countries (by mid-2000 Burkina Faso, Cameroon, Madagascar, Mali, Uganda, and Zambia).

The PEDA model has also inspired theoretically oriented scholars interested in the long-term dynamics of nonlinear models to develop a more general reduced form of the model that includes only a handful of variables and equations but maintains the nonlinear food distribution function (Lorenz curve). The explicit consideration of a concentration curve in this context seems to be an innovative feature with interesting consequences for the dynamic behavior of the model. This reduced model can complement the full empirical model in terms of sensitivity analysis and in gaining a better understanding of the nature of the underlying dynamics (Dworak et al. 2001). Hence, a specific feature of this chapter

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will be the comparison between the full PEDA model with an empirical application to Mali and the reduced-form PEDA, in order to learn some general lessons about the advantages of different degrees of complexity and detail in dynamic population-environment modeling.

After this introduction the chapter consists of three parts. First, the general approach, theory, and design of the full empirical PEDA are discussed and illustrated with selected scenarios for Mali. Next, we introduce the reduced-form model, develop comparable scenarios, and compare the model performance and sensitivity analysis of the full empirical and the reduced-form PEDA. In a final part we draw conclusions and discuss how the two ways of capturing the dynamics complement each other by serving different purposes.

The full PEDA model

Logic and structure of the model

A theoretical construction, often labeled the "vicious circle model," has recently become a very influential paradigm in the discussion around population, poverty, food security, and sustainable development. It assumes that high fertility, poverty, low education, and low status of women are bound up in a web of interactions with environmental degradation and declining food production, in such a way that stress from one of the sources can trap certain rural societies, especially those living in marginal areas, into a vicious circle of increasingly destructive responses. One illustration of this assumed mechanism is the parable of the firewood (Nerlove 1991). In many countries the collection of firewood takes a lot of time, and more children can help to collect more firewood. But this leads to less firewood near the villages, increasing degradation of the natural resource, and the desire for more children to go still further, also depriving the children of educational opportunities. Dasgupta (1993) presents this argument in a more generalized form. The condition of poverty and illiteracy of the households concerned prevents substitution of alternative fuel sources or alternative livelihoods. A gender dimension is added through the fact that the low status of women and girls also devalues the increasing amount of time and effort that they must devote to daily fuelwood gathering (Agarwal 1994; Sen 1994). The education of girls is blocked because girls are kept at home to help their mothers. The result is faster population growth, further degradation of the renewable resource base, increasing food insecurity, stagnating education levels, and yet a further erosion of women's status.

From a theoretical point of view this vicious circle model is a useful contribution toward a more general framework in causally linking fertility, poverty, low female status, and environmental degradation. It is also attractive because it explicitly addresses equity concerns. Its multi-dimensional structure helps to view different possible interventions in, for ex ample, reproductive health, education, environmental conservation, and agricultural efficiency in a unifying context rather than in isolation from each other. Each of the interventions may, under certain conditions, contribute to breaking up the vicious circle, but – as the following applications will show – a comprehensive strategy viewing all these aspects together and recognizing their interdependencies is likely to be more successful (O'Neill et al. 2001).

In terms of its empirical relevance, the vicious circle assumption is more controversial. Because the economic reasoning of this model largely operates at the household level, empirical studies on the issue have been mostly confined to that level and have reached mixed results. At the macro level of different population segments, this model could potentially be very relevant, especially in the African context, although some of the assumptions of the stricter version of this model are empirically unconfirmed and controversial. In particular the assumption that environmental degradation may actually lead to increases in fertility is difficult to defend at a time when fertility rates are rapidly falling all over Africa with simultaneously degrading environmental resources. This does not necessarily imply that the assumed effects are entirely absent, but it seems to imply that if they operate, they are overlaid by the powerful and dominating process of demographic transition. Hence, it may be reasonable to assume alternatively that food insecurity is associated with a slower decline in fertility, although under certain conditions and in the short run famines may well induce declining fertility. Whatever the position on this issue, the PEDA model as outlined below is general enough to represent alternative assumptions through alternative parameter choices and scenarios.

Figure I gives the basic structure of PEDA. The model has a rather open structure. But it can capture the basic assumed mechanism of the vicious circle, namely, that rapid population growth due to high fertility of the illiterate, food-insecure population in marginal rural areas contributes to further degradation of the land, thus lowering agricultural production and further increasing the number of food-insecure persons. If not broken this vicious circle would lead to ever increasing land degradation and in creases in the food-insecure population. This model does not assume in creasing fertility as a response. Rather the food secure and food insecure are assumed to have different fertility levels (or exogeneously defined trends), and hence the aggregate fertility level only responds to changing food insecurity through the changing weights of the groups. The vicious circle can be broken, however, through several possible interventions in the field of food production, food distribution, education, environmental protection, and population dynamics.

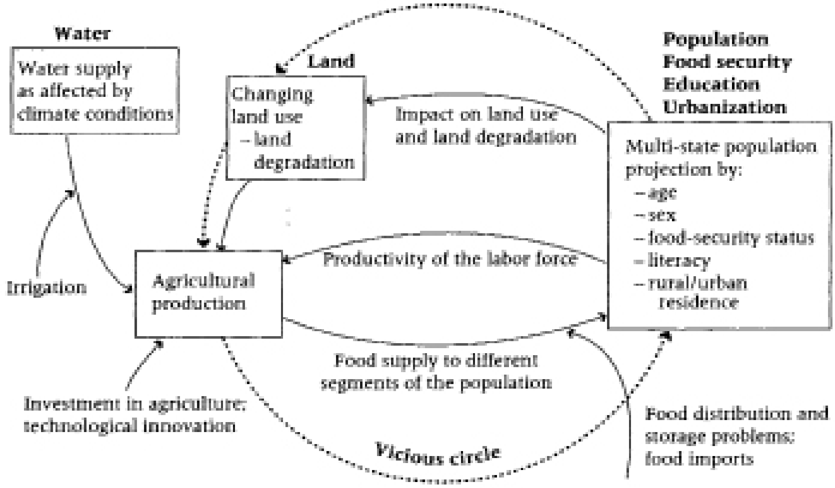

Figure 1. Basic structure of the PEDA model linking population, food security, and the environment in Africa

Note: In a vicious circle, high population growth of the rural food-insecure population contributes to degradation of marginal lands. This decreases agricultural production, which in tum increases the number of food-insecure persons.

Such a quantitative model can help policymakers and other users to (a) view these interconnected aspects, and (b) think in terms of alternative outcomes of alternative policy scenarios.

PEDA is different from most macroeconomic models in that it uses a population-based approach. The population-based approach views human beings and their characteristics (such as age, sex, education, health, food security status, place of residence, and the like) as agents of social, economic, cultural, and environmental change. But the population is also at risk of suffering from repercussions of these changes and of benefiting from positive implications. In this sense the human population is seen as a driving force of these changes and is affected by the outcomes and consequences of these changes. Economics, if it comes into the picture – for example, through the importance of markets in distributing goods – plays only an intermediate role and is not seen as an end in itself or the primary object of modeling. In this respect, the population-based approach chosen here differs from much of the development-economics literature.

The population-based approach does not assume that population growth or other demographic changes are necessarily the most important factors in shaping our future. It must not be misunderstood in the sense of a narrow view in which only demography matters. Instead the phenomena that we want to model are studied in terms of different characteristics that can be directly attached to and (at least theoretically) measured with individual members of the population. Characteristics such as age, sex, literacy, place of residence, and even nutritional status can be assessed at the individual level. The sum of these individual characteristics makes up the distribution in the total population. These individual characteristics are different from other frequently used indicators such as the GNP per capita, which, although it is suggestive of the average amount of money that an individual has in his/her pocket, cannot be directly measured with individuals. GNP results from a certain way of aggregate-level national accounting with various conceptual and measurement problems. Although many of the powerful quantitative economic tools (such as general equilibrium models) cannot be applied under our choice of approach, other very powerful but less well-known tools of demographic analysis and projection can be applied. The tools of multi-state population analysis allow for the projection of the population by several characteristics (such as age, sex, education, and place of residence) at the same time. Multi-state projection groups all individuals of a given population into different subpopulations, which are then projected into the future, while in each time interval, people can also move from one subpopulation to another (e.g., from rural to urban or from illiterate to literate for each sex and age group).

As shown in Figure 2, in PEDA the population of a country under consideration is broken down into eight sub-groups according to urban/ rural place of residence, education, and food-security status. Place of residence and food-security status are two dimensions that are core elements of the vicious circle reasoning as specified in this setting. Education, or more precisely literacy status, has been introduced into the model as one of the assumed key sources of population heterogeneity, which is related to both agricultural production and land degradation. Significant educational fertility differentials give the explicit consideration of education in the model a strong rationale. There is abundant literature on the significance of literacy in population-development-environment interactions (see, e.g., Lutz 1994). The potential of explicitly including education as a demographic dimension in multi-state population projection models has recently been evaluated (see Lutz et al. 1998) and is strongly recommended in the case of educational fertility (or other behavioral) differentials.

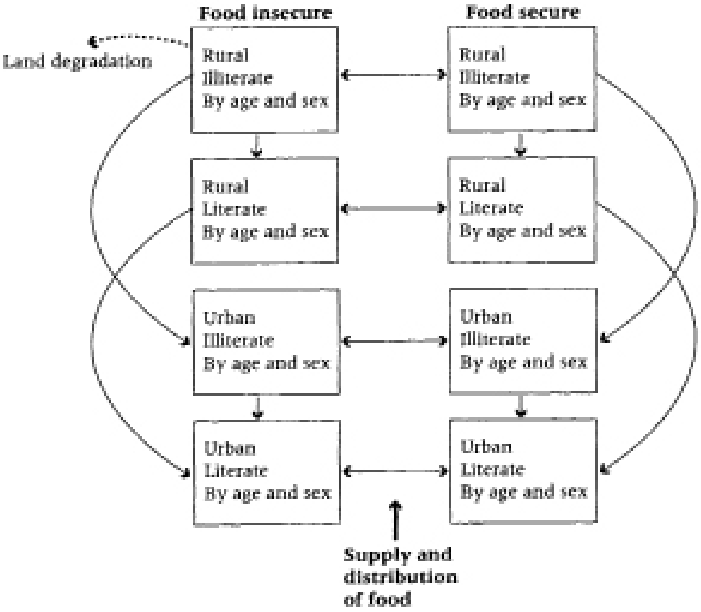

Figure 2. PEDA population segment: A multi-state model for Africa by place of residence, education, and food-security status

Each of these eight sub-groups further subdivides the population by age and sex, that is, every one of the eight groups has its own age pyramid. During each one-year simulation step, a person moves up the age pyramid by one year within the same subgroup, or moves to another subgroup while aging by one year. The movements between groups that are possible within each step are shown by arrows in Figure 2. For education and rural/urban migration, the model is hierarchical: people can only move in one direction, from lower to higher education and from rural areas to urban areas. Movement between food-security states can happen in both directions, de pending on the food conditions in the relevant year and the food distribution function.

This PEDA population module is in itself a useful piece of software (written in Excel) for multi-state population projections. For each of the eight states the user can set age- and sex-specific fertility, mortality, migration, and transition rates from one state to another. If such detailed empirical data are not available, standard age schedules can be applied and relational logit transformations are applied for mortality. More generally, each country first needs to be initialized in terms of all empirical data for the starting conditions. This is a significant task to be done outside the normal software, and it requires more demographic skills than the use of the initialized model, which is very user friendly in terms of scenario setting and presentation of results.

As indicated in Figure 1, the population module, that is, the population by age and sex in the eight defined categories and for each year in time, affects the total agricultural production in two ways. The productivity of the rural labor force as measured by the proportion literate of the rural population of productive age directly enters the agricultural production function as discussed below. The other chain of causation is a direct reflection of the vicious circle reasoning: the land factor is degraded as a function of the increase in the number of people in the rural, food-insecure, and illiterate category. In the current version of PEDA, this impact is operationalized in the following manner. The total amount of high-quality agricultural land enters the production function in an index form, which is assumed to combine quantity and quality aspects. The higher the increase (as compared to the starting conditions) in this critical group of food-insecure, rural, illiterate persons, the more this land factor will decline (cf. Eq. (9) in the Appendix). The user can set a scenario variable, the land degradation impact factor, that determines to what degree a certain percentage increase in this critical population influences the land index.

Agricultural output is calculated by a Cobb-Douglas type agricultural production function as estimated by Hayami and Ruttan (1971) for a number of developing countries. In addition to the rural labor force, literacy, and land, which are at least partly endogenous to PEDA, production also depends on fertilizer use, machinery, and technical education, which are treated as exogenous scenario variables. PEDA also includes a water component, which has a direct impact on production and which is also influenced by land degradation among other factors. The result of this process is the total amount of calories produced in the country in a year. (The details of the production part of the model are described extensively in Lutz & Scherbov 2000).

Unfortunately, in reality, not all production is consumed by individuals to satisfy their food needs. Some calories are lost during the treatment of food; others are lost during transport; and some are lost because of inadequate storage. Of the food that actually reaches people for consumption, a certain fraction goes to urban areas and another to rural areas. All these factors can be set in PEDA as scenario variables specific for a country and can be changed over time, or alternative starting values can be assumed. More specifically, in the model the user can set three scenario variables: loss in transport and storage, food import/export, and an urban bias factor. The last determines to what degree the total available food should be disproportionally distributed between urban and rural areas. Within these areas, however, not everybody will receive an equal amount of food. Reality shows that there are gross inequalities in access to food and, therefore, PEDA has an explicit food distribution module.

Even if the total amount of food reaching the urban and rural total population would be theoretically sufficient to provide the necessary mini mum diet for everybody, in practice the distribution of food is unequal because some persons have more purchasing power than others, or have privileged access to food by other means. This results in some people remaining food insecure even when the average total amount of food reaching the population is above the minimum.

Abundant empirical evidence backed up by theoretical considerations shows that the distribution of food is at least as important as the total production of food in explaining food insecurity. The work of Amartya Sen (1981) in particular demonstrated that some of the worst famines occurred under conditions in which theoretically there would have been enough food for everybody, if the distribution had been appropriate. For this rea son it is evident that a model focusing on food security without paying attention to the distributional aspects would be incomplete, if not misleading. The main problem with considering such distributions, however, is that hardly any empirical data exist on distributive mechanisms in the countries of Africa today, and theoretical distributions are hardly appropriate because conditions tend to vary significantly from one country to another. As a solution to this problem, in PEDA we chose to approximate the food distribution function through an income distribution function, which exists for a number of African countries based on household income surveys.

This allocation of food to urban and rural populations and the food distribution within these populations then determine the new sizes of the foodsecure and food-insecure subpopulations in the following year.

Figure 3 shows such a food distribution function that is applied after allocating the total available food to urban and rural populations (according to an exogenously defined "urban bias" variable). This figure shows a Lorenz curve with the cumulated proportion of the population on one axis and the cumulated calories available for distribution on the other. The avail able food is then distributed from right to left along the black curve. The given curve indicates that in this case, the first (most privileged) 10 percent of the population use 30 percent of the available food. Going further down the curve, about 23 percent of the population use half of the food, and half of the population uses 75 percent of the food. The borderline between the food-secure and the food-insecure population is then established by applying an externally defined minimum calorie requirement per person. At the point where the consumption per person falls below the mini mum requirement, the borderline for the population considered to be food insecure is established. Over time the proportions food insecure may change as a consequence of changes in the calories available for distribution or possible changes in the assumed food distribution function.

Alternative scenarios for Mali

To give a concise example of an actual application of PEDA, we chose Mali, a country with serious land degradation problems, a total fertility rate of 6.6, and an estimated proportion of food insecure of around 30 percent. To compare the consequences of alternative future trends for the country, we defined six scenarios for Mali from the starting year 1995 (latest data available) up to the year 2030.

Scenario 1: All rates remain constant at their 1995 level.

Scenario 2: Fertility in all groups declines to half of its 1995 level by 2030; all other rates are constant.

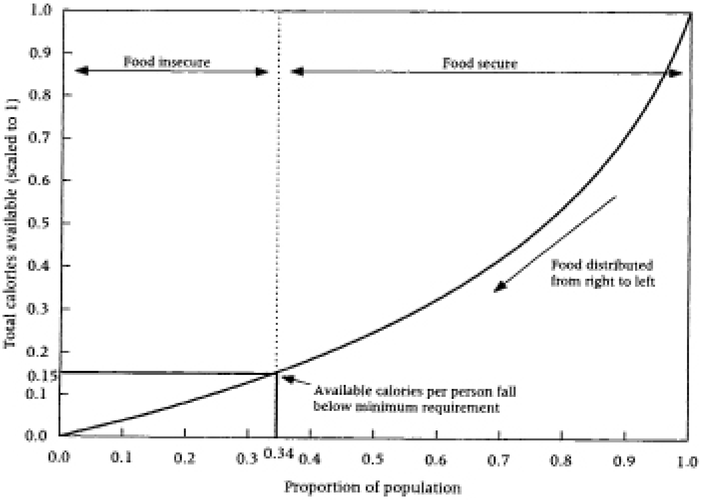

Figure 3. Food distribution function

Scenario 3: In addition to the fertility decline as in scenario 2, primary school enrollment rates increase to 80 percent immediately, that is, 80 percent of young cohorts become literate.

Scenario 4: On top of the assumptions of scenario 3, civil unrest (or other problems) results in a loss of 30 percent of the harvest for the years 2005-09.

Scenario 5: Fertility declines to 2.2 (on average) by 2020; 80 percent of young cohorts become literate; otherwise like scenario 1.

Scenario 6: Like scenario 5, but fertilizer use also increases by 1 percent per year.

These six scenarios result in very extensive output tables. Detailed results for single-year age groups could be studied for each of the eight subpopulations or any combination of them, for example, food-insecure illiterate rural women between ages 60 and 65. In terms of human welfare the most interesting aggregate-level result is probably the evolution of the proportion food insecure.

Figure 4 depicts the trend in the total proportion food insecure under the six alternative scenarios. Since the graph is on a relative scale, one needs to know that under scenario 1 (constant rates) the total population of Mali would increase from 9.7 million in 1995 to 31.7 million in 2030. Because of the great momentum of population growth, even under the fertility decline scenario (scenario 2), total population would increase to 23.1 million, and under extremely rapid fertility decline (scenario 5) total population would still almost double to 17.6 million by 2030. For the first two scenarios food security deteriorates significantly over time, even though an assumed fertility decline (scenario 2) would ameliorate the situation. Additional strong educational efforts (scenarios 3 and 4) clearly make a significant difference, and the proportion food insecure only increases to somewhat above 40 percent. This is because education has three partly independent beneficial effects on food security: it increases productivity, it retards land degradation, and it reduces population growth through a higher proportion in the more educated subpopulations that have lower fertility. Scenario 4, which assumes a temporary problem in terms of loss of food, has a clearly visible negative effect on the graph, but has insignificant lasting consequences. A sustainable

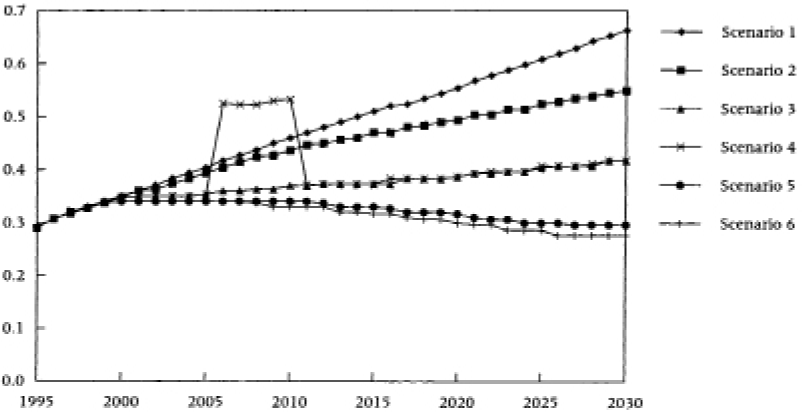

Figure 4. Trends in the total proportion of the population that will be food insecure in Mali under different scenarios

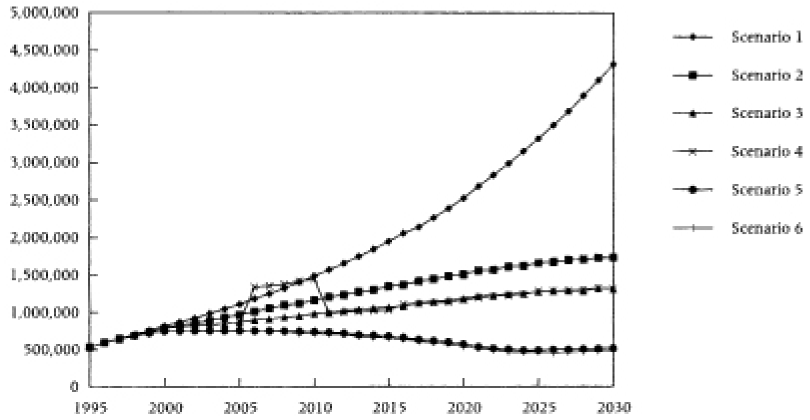

Figure 5. Trends in the absolute numbers of children aged o-4 that will be food insecure in Mali under different scenarios

stabilization in food security, however, results only from scenario 5, which assumes an even more rapid fertility decline to 2.2 by 2020. If improvements in fertilizer use (scenario 6) are added to that, then the situation improves in the longer run.

Figure 5 shows the same six scenarios for the absolute number of food insecure children below age 5 years in the whole of Mali. The picture has the same qualitative structure as Figure 4. Under the (unrealistic) constant rates scenario, the absolute number of food-insecure children would increase by an incredible factor of more than 8. Here the difference between scenarios 1 and 2 (fertility goes to half the level by 2030) is already very significant and would result in less than half of the number of food-insecure children. Education also makes a difference, but less strongly than in the case of total proportions food insecure. Finally, increased fertilizer use makes little difference with respect to the number of food-insecure children. In conclusion the comparison between Figures 4 and 5 shows that for the absolute number of children who will be food insecure, the assumed level of future fertility is of overriding importance, whereas for the total proportions food insecure, education and some of the technical inputs such as fertilizer use also have considerable impact.

The applications of the full empirical PEDA model to different African countries under large sets of alternative assumptions have been extensively described elsewhere (Lutz & Scherbov 2000). In the context of this chapter it was our intention to outline the basic structure and philosophy of the model and give a taste of its potential for applications. This now allows us to compare the model to a highly reduced form of PEDA with much lower empirical content and complexity, but higher flexibility and transparency.

Set up and assessment of a reduced-form PEDA model

When deciding on a reduced-form model we have to keep in mind that the specific context determines the degree of aggregation. Because the food distribution function is a key feature that governs the dynamics in the PEDA model, we aim to build up a reduced-form model that focuses on gaining a better understanding of how the degree of inequality in food distribution affects population and resource dynamics and their interactions, and reduces complexity in the other parts of the model.

In the reduced model we therefore disregard the urban population (which in PEDA is not involved in food production) and consider only the rural food-secure population P_S and rural food-insecure population P_I. We also aggregate over education, age, and sex. This simplification comes at the cost of losing age-structural impacts such as momentum, as well as the possibility of looking at age and sex differentials of the results. But since we want to focus primarily on the food distribution mechanism, the significant reduction in the number of population states from 1600 (8 states x 2 sexes x 100 age groups) to just two (food-secure and food-insecure rural population) seems to be worth the costs. In addition to these two population stocks, the reduced-form model also includes the resource stock R which corresponds to land in the full PEDA model, as the third dynamic variable. All other exogenous production factors such as water, investment, fertilizers, and food adjustments through imports and storage losses are aggregated into the technology parameter of the food production.

The basic structure of the reduced-form PEDA model is sketched in Figure 6 (a detailed summary of the equations of motion of the reducedform model can be found in the Appendix). For each time period, the stock of rural food-secure P_S and rural food-insecure P_I populations, together with the amount of available resources R, determines the total food production. The stock of resources will in turn depend on indigenous resource growth and previous degradation as caused by the rural food-insecure population and the prevailing population density. Because food is not equally distributed among the population, and some minimum level of calories is necessary to be food secure, the prevailing food distribution will determine the proportion of the population that becomes food insecure or food secure for each time period. Together with the prevailing natural growth rates of the population, the movement between food security and food insecurity status will determine the next period's stocks of the rural food-secure and rural food-insecure populations.

To calibrate the reduced-form model so that it matches the full empirical model, we first run the full empirical model, using the same functional forms for the Lorenz curve, resource dynamics, and production function as summarized in the Appendix. Additionally, all transitions between rural/urban and literate/illiterate population states have been set

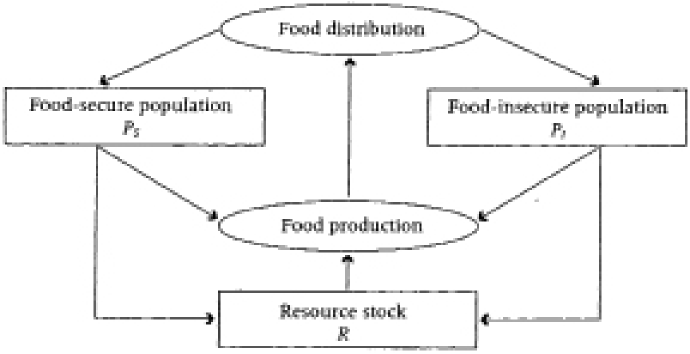

Figure 6. Reduced-form PEDA model

Note: The population stock of the food-insecure and food-secure rural populations has been scaled to the initial stock of the whole rural population, i.e., $P_1(t)/P(O), P_s(t)/P(O)$. Resources are scaled to start at the value of $R(O) = 1$. Parameters have been set as in Figure 7a.

equal to zero, and all production elasticities except those for resources and labor are set equal to zero in the production function. From the resulting time series of rural population states by age and sex, we construct the time series of the total stock of rural food-secure and rural food-insecure populations. The corresponding time series of births and deaths for rural food secure and rural food-insecure populations can then be used to construct the natural population growth rates of each subpopulation. Next, we run the reduced-form model with the exogenous time series of the population growth rates as obtained by the empirical model. The other parameters, as well as the initial conditions for the rural food-secure and rural food-insecure populations and the resource stock, have been set according to the empirical model. Obviously, after this calibration, the reduced form model produces results very similar to those of the empirical model.

In Figures 7a-7c we plot the time series of the food-secure and food insecure rural populations, and the resource stock for the full empirical and the reduced-form model for various degrees of inequality in food distribution as measured by the parameter α (see Appendix, equation (5)). If $\alpha = 1$, everyone in the economy will receive the mean income, that is, “per-feet equality” will prevail. Values of α greater than one imply that total production is not equally distributed among the population, with larger values of α implying a more unequal food distribution.

Choosing Figure 7a as the baseline scenario, Figures 7b and 7c demonstrate the effect of reducing or increasing the degree of inequality in food distribution, respectively.

The results clearly demonstrate that environmental degradation and population dynamics are closely interlinked with institutional settings as represented by the food distribution function. When food is more equally distributed among the population, the share of the food-insecure population will be lower, and the pressure on the resource stock will be less (see Figure 7b). A very unequal food distribution (Figure 7c) may initiate the vicious circle between population growth and environmental degradation.

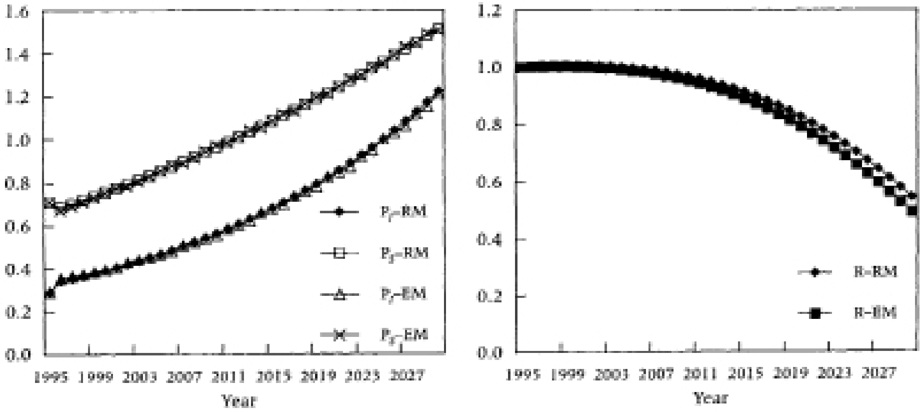

Figure 7a. Simulations of food-secure and food-insecure rural populations and resources for the reduced form model (RM) and the full empirical model (EM) with the degree of inequality infood distribution set at $\alpha = 2.667086$

Note: The population stock of the food-insecure and food-secure rural populations has been scaled to the initial stock of the whole rural population. i.e., $P_1(t)/P(O), P_s(t)/P(O)$Resources are scaled to start at the value of $R(O) = 1$. Parameters have been set at $a = 0.02$, $\bar{R} = 1.5$, $\gamma = 0.02$, $n = 1$, $T = 2.912$, $\beta_1 = 0.088$, $\beta_2 = 0.534$, $y^* = 1.2$.

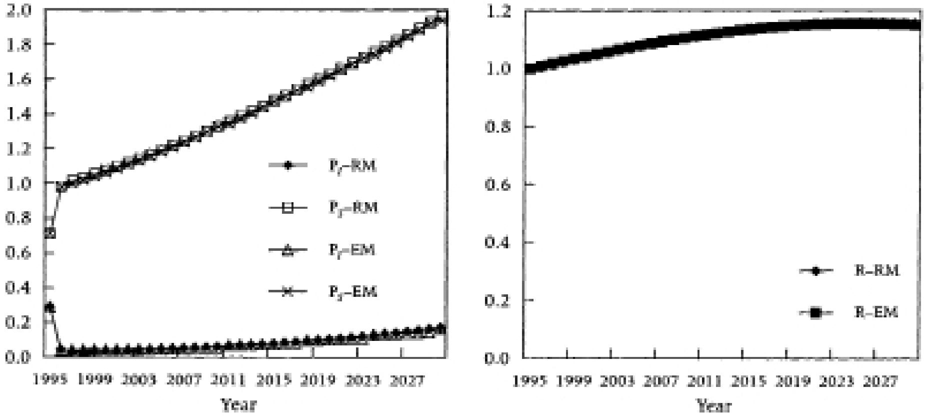

Figure 7b. Simulations of food-secure and food-insecure rural populations and resources for the reduced form model (RM) and the full empirical model (EM) with the degree of inequality in food distribution set at $\alpha = 1.334172$

Note: The population stock of the food-insecure and food-secure rural populations has been scaled to the initial stock of the whole rural population. i.e., $P_1(t)/P(0), P_s(t)/P(0)$. Resources are scaled to start at the value of $R(0) = 1$. Parameters have been set as in Figure 7a.

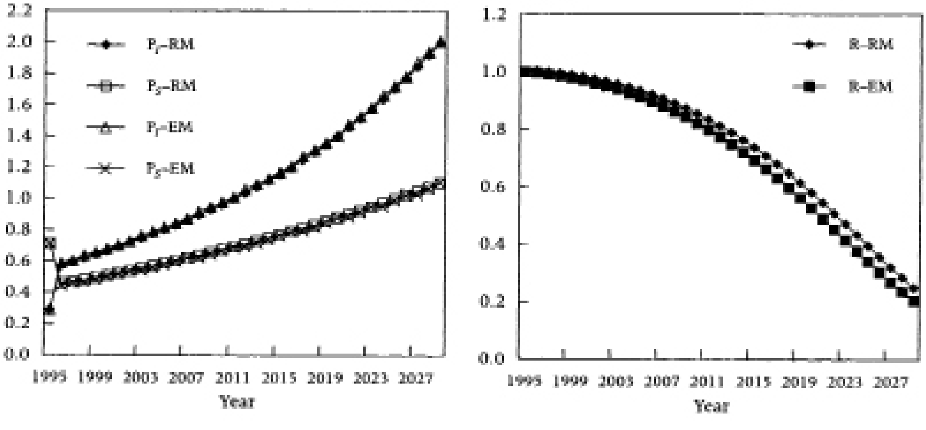

Figure 7c. Simulations of food-secure and food-insecure rural populations and resources for the reduced form model (RM) and the full empirical model (EM) with the degree of inequality in food distribution set at $\alpha = 5.334172$

The correspondence between the full empirical model and the reducedform PEDA model is very persuasive, even more so since we did not recalibrate our reduced-form model when we changed the form of the food distribution function in Figures 7b and 7c. More specifically, we ran the reduced-form model with the same exogenous natural population growth rates as in Figure 7a, and varied only the parameter of the food distribution function in Figures 7b and 7c. In the full empirical model, any change in the form of the food distribution function will feed back on the natural population growth rates of each subpopulation. Even though we keep fertility and mortality constant in the full empirical model as well, the transition between population states will affect the age composition and hence forth the number of births and deaths. But as our reduced-form model shows, these compositional changes in the age structure may not be very strong, at least not for the range of parameter values we consider.

The simulations in Figures 7a-c demonstrate various important roles of reduced-form models. We can use such aggregate models to better understand in which way changes in, for example, food distribution will affect the dynamics of population structures and natural resources. That there will be effects is obvious, but it is equally important to understand whether such effects will mainly work through the transition between population states or whether they might feedback on population processes such as the natural population growth rates. Although we do not recalibrate the population growth rates, we nevertheless get quantitatively similar results for the reduced-form and the full empirical models in Figures 7b and 7c. This indicates that changes in the food distribution function mainly affect the composition of population states as opposed to the age composition of various population states. Hence, the sensitivity analysis conducted in Figures 7a-c acts as a test of whether the reduced-form model is adequate to investigate the role of food distribution, and thereby contributes to a better understanding of the underlying mechanisms.

Once we have set up a reduced-form model that yields qualitatively the same dynamics as the full empirical model and have investigated whether this qualitative equivalence persists under specific sensitivity analysis, we can use the reduced-form model to investigate the spectrum of possible dynamics. Not only can we perform simulations much faster by running a reduced-form model, but we may also be able to explicitly derive analytical expressions. The latter suggestion is most relevant when we con sider the long-run behavior of our model. While the transient behavior may be very sensitive to parameter changes, the long-run values of the population and resource stock may be very stable across various parameter changes.

Recalling the equations of motion of the rural food-secure and rural food-insecure populations as stated in the Appendix, we can easily verify that for positive values of the natural population growth rates, the system does not yield any sustainable long-run equilibrium. More specifically, since population grows exponentially and resources grow only logistically, re sources will tend toward zero in the long run, while the whole population becomes food insecure. To facilitate a sustainable long-run equilibrium with a positive value of the resource stock in the long run, we have altered the total fertility rate of the food-secure and food-insecure populations to 1.5 and 3.0, respectively, while keeping all other parameters as in Figure 7a. Simulations of the full empirical model and aggregation over age, sex, and education as outlined above imply that for this alternative scenario the population growth rates of the food-secure and food-insecure rural populations decline to $n_S = -0.015$ and $n_I = 0.006$ by 2030.

We then use these values of the population growth rates together with the parameter setting in Figure 7a and iterate the reduced-form model until the system converges to an equilibrium with constant stocks of food secure and food-insecure rural populations and resources. However, even for this alternative parameter set, the reduced model converges to an unsustainable long-run state. Contrary to the case where both population growth rates are positive and the system converges toward a state where resources become extinct, now the resources equilibrate at their carrying capacity $\bar{R}$ and population becomes extinct (compare Figure 8a). By analytical calculations it can be verified that in addition to the unsustainable long-run equilibrium depicted in Figure 8a, there may exist a sustainable equilibrium for the same parameter values with strictly positive values of food-secure and food-insecure rural populations and a positive level of resources below the maximum carrying capacity (compare Lutz et al. 2000, Appendix B). Obviously this sustainable equilibrium must either be unstable or be separated by a third unstable equilibrium, since we would have otherwise converged toward this equilibrium by applying forward iteration of our reduced-form model. In Lutz et al. (2000 Appendix C) we present a more in-depth investigation of this sustainable equilibrium as it depends on the degree of inequality in the food distribution. In particular we show that this sustainable equilibrium is unstable over the range of values of the degree of inequality in the food distribution we consider; that is, one will never converge to the sustainable equilibrium except in the nongeneric case of starting on a particular manifold that is associated with the unstable equilibrium. However, the long-run equilibrium value toward which the system converges may change depending on the degree of inequality in food distribution. By increasing the degree of inequality in the food distribution (Figure 8b) but keeping all other parameters as in Figure 8a, the system ends up in a situation where resources will vanish in the long run and all population ends up being food insecure.

Summing up, although we have analytically shown that there might be a sustainable long-run equilibrium with positive values of population and resources in the event that the population growth rate of the food-insecure population is negative, the system will not converge toward this equilibrium since it is unstable. In the long run the system will converge either toward a situation where resources are depleted or toward a situation where population becomes extinct. Hence, there is no sustainable (in terms of positive values of both population and resources) alternative to the vicious circle in the case of the parameter settings that underlie Figures 8a and 8b. The degree of inequality in the food distribution and the initial conditions of population and resources, where the system starts off, will determine to which of the two unsustainable equilibria the system will converge.

How can we interpret these results? Recalling that we assume a negative rate of population growth for the rural food-secure population and a positive rate of population growth for the rural food-insecure population, the following situation results. In the case of low values of α (Figure 8a), part of the rural food-insecure population will become food secure in each time period. But as the rural food-secure population declines over time, food availability for the rural food-insecure population increases over time and reinforces the transition toward food-security status. Hence, in the long run, the whole population will become food secure; this is the population that ultimately vanishes as its natural population growth rate is negative. On the other hand, if inequality in food distribution is high (Figure 8b), only a small proportion of people will move from food-insecurity status toward food-security status. This proportion may not be sufficient to counteract the indigenous decline of the rural food-secure population, nor may it relieve the population growth of the rural food-insecure population over time. Hence, a vicious circle of increasing food insecurity and environmental degradation may set in with the rural food-secure population vanishing in the long run.

What is the message conveyed by the long-run dynamics of the reduced model as illustrated in Figures 8a and 8b? One of the most important lessons is that a focus only on transient sustainable paths of population and resource dynamics is dangerous. Although the statement by Keynes (1923, p.65), “In the long run we are all dead,” is persuasive for today’s society, the irreversibility of resource degradation cannot be neglected, and the responsibility of today’s society, therefore, has to exceed the life span of an individual. Hence, consideration of long-run dynamics is especially justified in research on population-environment interrelationships.

By offering alternative scenarios for long-term development of resources and population, we can draw attention to the sensitivity of the model assumptions with regard to specific parameter values and/or functional forms. For instance, for the parameter values chosen in Figures 8a and 8b, a sustainable future is guaranteed only if we start our simulations either exactly in the unstable equilibrium that corresponds to the only sustainable equilibrium or on a particular manifold associated with this equilibrium. However, the dimension of this manifold is less than that of the state space and therefore this case is nongeneric. Any deviation from the sustainable equilibrium will imply convergence toward one of the unsustainable long-run equilibrium states as illustrated in Figures 8a and 8b. Although the interpretation of the long-run dynamics as outlined above seems almost obvious and not really surprising, a mere sensitivity analysis of the full empirical model would be much more difficult and less intuitive.

It should be noted that the existence of one sustainable long-run equilibrium that is unstable and two alternative long-run equilibria that are unsustainable in terms of either resources or population is not unique to the general set up of the PEDA model. The result depends on the assumptions about the fertility and mortality of the food-secure and food-insecure populations. As shown in Dworak, Prskawetz, and Feichtinger (2001) endogenous population growth rates that incorporate feedback from the environment and the economic structure may aid a sustainable long-run equilibrium where population and resources are positive.

Conclusions

A computer model is a tool to extend the capabilities of the human brain. Similar to using a pencil (or a keyboard for text processing) for writing down notes on thoughts that we will not otherwise be able to remember, a computer can help us to consider more things simultaneously than our brain is usually able to do. A second advantage of a computer model over the human brain is that the assumptions and steps that lead to a result are completely transparent and can be repeated by anybody interested in doing so. Similar again to the pencil (or a keyboard), thoughts and relation ships are being nailed down in a lasting and open manner. This is some thing the human brain, even aided by speech, cannot do.

In the field of population and environment analysis – as in many other fields – it is therefore the wrong dichotomy to ask whether one should use either computer models or other more qualitative or anthropological approaches. It is simply a matter of choosing the right tools for a given re- search question. If the objective is to anticipate future trends or give warning of pending dangers in a quantitative way that is explicit, so that it can be repeated by others, then the choice of tool will most likely be a computer model. But this is not the end of the decision process because there is an infinite number of possible specifications of computer models, even for specific future-related questions.

While the questions of choice of variables, regional focus, and level of regional aggregation can usually be resolved in a straightforward way, depending on the context of the question asked, in this chapter we address one of the more difficult issues, namely that of the appropriate level of complexity and empirical content.

In judging the usefulness of reduced-form models versus full empirical models, it is useful to recall the recent debate in the population fore casting literature on "simple versus complex models" (Rogers 1995b). "The most fundamental rationale for disaggregation is the demographer's eternal hope that, when the right disaggregation is discovered, temporal

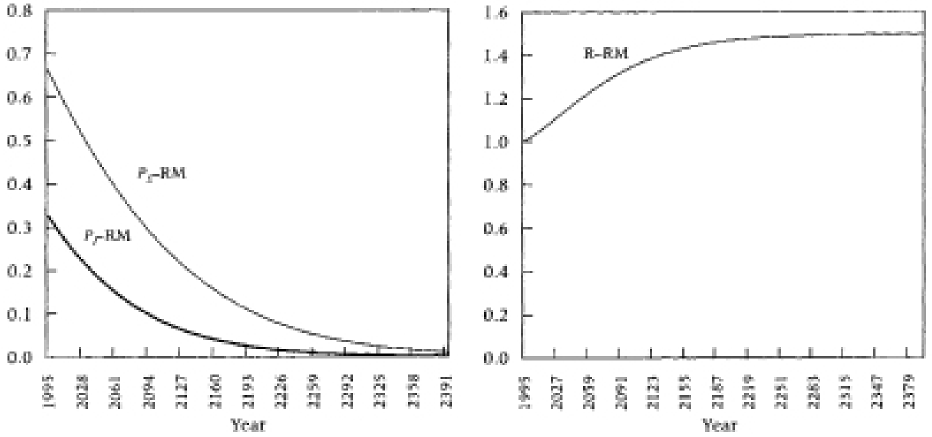

Figure 8a. Long-run behavior of rural food-secure and rural food-insecure populations and resources for the reduced model, with the degree of inequality in food distribution set at $\alpha = 2.667086$

Note: The population stock of the rural food-insecure, and rural food-secure populations and rural total population has been scaled to the initial stock of the whole population, i.e., $P_1(t)/P(O), P_s(t)/P(O)$, and $P(t)/P(O)$. Parameters are set as in Figure 7a except $n_1 = 0.005528$ and $n_5 = -0.00153$.

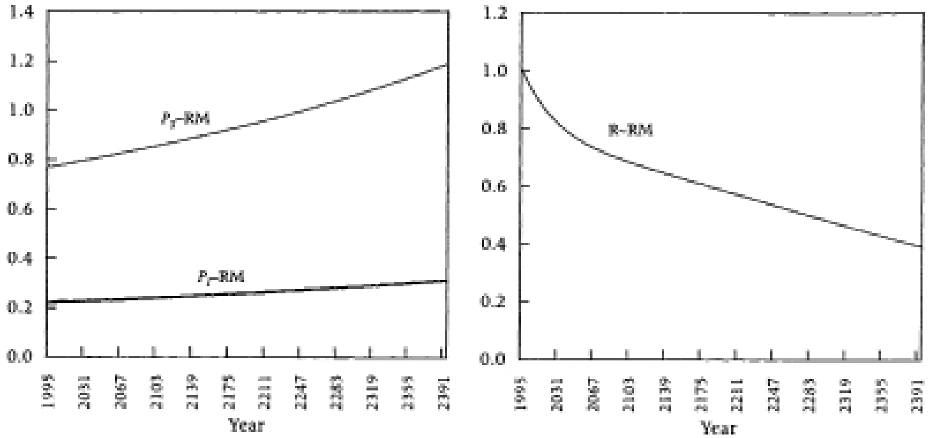

Figure 8b. Long-run behavior of rural food-secure and rural food-insecure populations and resources for the reduced model, with the degree of inequality infood distribution set at $\alpha = 15$

Note: The population stock of the rural food-insecure, rural food-secure populations and rural total population has been scaled to the initial stock of the whole population, i.e., $P_1(t)/P(O), P_s(t)/P(O)$, and $P(t)/P(O)$. Parameters are set as in Figure 8a.

changes that initially appear disorderly will be resolved into the effects of a distorted underlying structural composition applied to constant, or at least smoothly changing, refined rates" (Lee et al. 1995, p.218). Multi-state population models, such as the population component of the PEDA model, are partly based on this assumption. When studying the process of changing food security disaggregated by age, sex, and education (assumed to be important sources of heterogeneity), we hope to produce a more accurate estimate of the future food-secure population than would result from the simple projection of a population that is assumed to be completely homogeneous. For total population size, Lutz, Goujon, and Doblhammer-Reiter (1998) have recently shown that explicit consideration of educational groups in addition to age and sex tends to make significant differences for the projected total population size, especially for populations with strong educational fertility and mortality differentials and re cent improvements in school enrollment. This discussion, however, only concerns different sources of heterogeneity, assuming that one is interested solely in the aggregate outcome. If there is interest in the relative status of women, of specific age categories, or of certain educational groups, then there is no alternative to the explicit consideration of these dimensions. Increasing female education can only be considered as a strategy and studied in terms of its consequences in a model that includes female education. But Lee, Carter, and Tuljapurkar (1995, p.220) also note: "More complex disaggregations may simply conceal dynamic regularities that would otherwise be apparent." This aspect best captures the rationale of the reduced-form PEDA model. It refers to the danger of not seeing the forest for the trees. On the other hand, there is no forest without trees, and the aggregate picture in the end results from the sum of individual behaviors. Obviously, both the forest and the trees matter.

What does this tell us about the relationship between reduced and full models? If we can verify that the qualitative dynamics persist under the processes of aggregation and reduction, then the reduced-form model helps to elucidate the sensitivity of the dynamics as depending on parameter changes. Moreover, the reduced-form model may help us to derive analytical expressions for long-run values of the state variables and thereby facilitate comparative static analysis.

A strongly reduced model can never replace a full empirical model; it should serve rather as a complementary tool to (a) gain more insight into specific dynamics, and (b) aid numerical sensitivity analysis. Hence, we should neither become a victim of the fallacy of "simple is beautiful" nor believe that adding complexity always improves understanding. For the researcher in population and environment analysis, judgment should be based on analysis of models of differing complexity. And here, human in tuition, experience, and considerations of plausibility must also enter.

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5 Applications of Multistate Demography/Methods

Introduction

Frans Willekens

Sergei Scherbov came to IIASA in 1982 as a member of the Institute's Young Scientists Summer Program (YSSP). He joined the former Human Settlements and Services (HSS) area at a time when the Migration and Settlement Study was in full swing. In that study, which was initiated and coordinated by Andrei Rogers, methods of multiregional demography were being applied to explore internal migration and population distribution patterns in the 17 member countries of IIASA. The application of a common methodology in international comparative research facilitated international comparison and the diffusion of new research methods. The study included multiregional population projections under constant rates of fertility, mortality, and migration. Flexible and user-friendly software for multiregional demographic projection did not exist at the time. Sergei took on the challenge of turning the projection model into a simulation model and a flexible tool for exploring the demographic consequences of varying fertility, mortality, and migration rates.

Sergei aimed at developing a flexible and interactive system for multiregional forecasting. His background in systems theory and control sciences and his expertise in demographic modeling resulted in a unique combination of skills to meet that challenge. Flexibility was ensured by a utility that allowed flexible scenario setting in terms of summary indicators or detailed, age-specific, rates. Scenarios could be prepared in advance and entered as text file or they could be specified interactively (i.e., during simulation runs). The human-computer interaction was a major innovation. In cooperation with Hartmut Usbeck, another Young Scientist in the Human Settlements and Services area, Sergei applied the new projection methodology and software to explore future migration and settlement patterns in the German Democratic Republic, one of IIASA's member countries. A total of six scenarios were produced, in addition to a base scenario (Scherbov & Usbeck 1983, this volume). As the Migration and Settlement Study was approaching its completion, the focus shifted to dissemination. Short courses were organized in Primorsko (1983) and Moscow (1985) and Sergei played a central role in the organization of these and the teaching.

After that initial period, Sergei continued to develop a flexible, interactive system for multiregional population projection and an extension to provide more general multistate projections. The projection model was a two-sex model, which was a major extension compared to the one-sex model used in the Migration and Settlement Study. Sergei called the new system a *dialog system* to reflect the interactive modeling and simulation approach. The dialog system implemented two additional innovations, which are common today but were very exceptional at that time: visualization and data exchange (data sharing between different computer programs). It was exceptional in that the dominant programming language at that time, Fortran 77, did not include the facilities or functions that are commonplace today. For instance, plotting required a special software package. The dialog system included an interface that controls the plotting package, for example, starts execution of the plotting package from within the dialog system and transfers data in the appropriate format. The system was developed for IIASA's VAX computer (Scherbov et al. 1986, this volume). Later, a microcomputer (PC) version of the dialog system was developed (Scherbov & Grechucha 1988, this volume). The flexibility of scenario-setting was extended. Instead of specifying summary indicators (such as TFR) every year, different trends could be modeled. The package was written in Fortran 77 and the NOLIMIT library was used to develop the interface and to standardize procedures. Later (after 1988), some modules (routines) were written in C for flexibility and speed. At that time, programming was an art as much as a science. Sergei mastered the art and the science more than anyone I know.

A major challenge at that time was to make the multistate projection system independent of the machine used. Software compatibility was a huge problem constraining portability. Sergei managed to overcome the problem. As a result, the package, which was named DIALOG, was used at several institutes in different countries. DIALOG included some context-sensitive online help, a major innovation at that time.

The development of an interactive system was a major advance at a time when batch processing and data entry at the DOS prompt was the norm. Windows and the technology for interactive processing had yet to be developed. The system Sergei developed to enable interaction with data (in multiple files) in real time was a forerunner of the distributed databases that are becoming standard today. Interactive processing is known today as interactive analytics. Sergei's vision in the early 1980s of a system for human-computer interaction that facilitates analysis and forecasting was remarkable.

DIALOG became the basis for the multistate projection models for which IIASA became famous. It was used to prepare marital status and family status scenarios for Austria in Gonnot et al. (1995), world population scenarios in Lutz et al. (1996; 1997, this volume), demographic scenarios for Mauritius (Prinz 1990) and population projections for Russia and 49 oblasts (regions), six krays (territories), 21 republics, one autonomous oblast, and two national cities (1997; 1998).

Sergei made significant contributions to multistate population projections. Some have been mentioned already. A tricky issue in multistate analysis is the aggregation of state-specific demographic indicators (e.g., the life expectancy). We may, for instance, have region-specific mortality rates by age and be requested to compute life expectancies by region and provide the life expectancy at the national level. The life expectancies by region can easily be computed from the regional death rates. The life expectancy at the national level is the weighted average of the life expectancies by region. But what weights should be used, in particular if people can move freely between the regions? Sergei and Wolfgang Lutz addressed that question and found that life expectancy should be calculated from the aggregation of regional deaths and regional populations by age. They concluded that the procedure used in some countries and also for several years by the United Nations to derive the life expectancy at the national level by weighting regional life expectancies according to the regional numbers of births is not an appropriate method (Lutz & Scherbov 1992; Andreev et al. 1989, this volume).

Another recurrent issue that has preoccupied researchers is how far one can disaggregate a population without producing erratic results. Subpopulations should be of sufficient size to permit the estimation of age-specific demographic rates and the derivation of summary indicators. Sergei and Dalkhat Ediev used simulation to determine a lower threshold of population size for computation of the life expectancy (Scherbov & Ediev 2011, this volume). Small populations lead to large standard errors for age-specific death rates and the life expectancy. The standard error is obtained using the common assumption that death counts by age follow a binomial distribution. The authors simulated populations of different size. Deaths were drawn from a binomial distribution with the probability of dying as the parameter. Standard errors and biases were estimated from the simulated populations. These found that, for populations of less than 5,000, the standard errors are high and are not normally distributed. Life expectancies should not be computed for such small populations. The normal distribution can be assumed for populations exceeding 50,000.

Sergei made major contributions to multistate demography and pioneered interactive systems in demography, in which analysts interact with the computer in real time to advance modeling, analysis, forecasting, and impact assessment. Sergei made many other fundamental contributions, several of which are listed in this volume. I would like to refer to one that may not be mentioned elsewhere. Sergei was instrumental in securing continuity in the release and publication of demographic data during the period of transition from the former Soviet Union to Russia and the other members of the Commonwealth of Independent States. Without Sergei's involvement and skills, it would not be possible today to study the demographic change during that transition. In the years prior to the mid-1980s, data availability on the USSR was limited. That changed in 1987 when the USSR State Committee on Statistics (Goskomstat SSSR) published the *Population of the USSR 1987*. Similar publications were released in 1988 and 1989. The first *USSR Demographic Yearbook* was published in 1990. In1991 the USSR ceased to exist. The uninterrupted publication of statistical data was in danger. Sergei, who at that time was at the Population Research Centre, University of Groningen, worked hard with Andrei Volkov and his colleagues at Goskomstat to ensure the uninterrupted publication of the Demographic Yearbook. It resulted in the *Demographic Yearbook of Russia 1991* and the *Demographic Yearbook of the Commonwealth of Independent States 1991*. The Demographic Yearbook of Russia continues to be published.

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Foreword by Douglas Wolf to "DIAL" - A system for modeling multidimensional demographic processes, S. Scherbov and V. Grechucha, IIASA, Working Paper WP-88-36[1]

Foreword

Multistate mathematical demography, much of the development of which took place in IIASA, has proven its usefulness in a broad range of applications including the analysis of migration, marriage, fertility, working life and household dynamics. Among other things the method makes possible the calculation of population projections which are disaggregated by region (marital status, parity, occupation, etc.). The following paper serves as a user's guide to a new microcomputer program which greatly facilitates the use of the multistate projection mathematics. A user with access to the appropriate data and modest skills with a computer can explore the future path of a population under a variety of assumptions about the direction of change in key variables. Graphical displays of results, and interactive updating of assumptions, also contribute to the usefulness of the system. The program described here has already been installed and used in a number of research institutes in several countries.

Douglas Wolf
Deputy Leader Population Program

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Dialog System for Modeling Multidimensional Demographic Processes[1]

Sergei Scherbov, Anatoli Yashin and Vladimir L. Grechucha

1. Introduction

A growing understanding of the importance of demographic processes in social and economic development places greater demands on the quality of demographic research and on the adequacy and convenience of tools used in the analysis of a population's characteristics.

Multistate population models recently became popular in the study of many aspects of demographic transitions, such as migration, marriage, changes of health status, social status, occupation, etc. (Keyfitz 1980; Yashin 1977).

Computer programs and software packages were developed to realize such models (Willekens 1979; Willekens & Rogers 1978). However, most of these allow analysis of systems only when fertility, mortality, or transition coefficients do not depend on time. Some authors have overcome this drawback (Ramachandran 1980; Scherbov & Usbeck 1983) and have created the opportunity to analyze alternative evolutions of the system under various scenarios of natural and mechanical reproduction of the population. However, these programs are not always appropriate for use by the many demographers and health specialists who are not deeply involved in computer modeling. The software is often not flexible enough to enable choices of and changes in the variables that determine the scenarios, the representation of the results, and the control of modeling itself.

The most important disadvantage of these packages is the inability to communicate interactively with the model. As experience shows, interactively working with computers essentially reduces the time spent on model design and debugging. It also creates additional opportunities for model analysis.

Thus, there is a necessity to create a user-friendly system that allows a more effective analysis of demographic processes.

In this paper an interactive system that uses the multistate demographic models is described. The system provides the opportunity to prepare scenarios, change coefficients of the model during the modeling procedure, and present intermediate results. The paper uses some results of research conducted at VNIISI and at IIASA: namely, the design of the man-machine modeling system (Gelovani 1980) and the modeling of multistate demographic processes (Rogers 1975; Scherbov & Grechucha 1984; Willekens 1979; Willekens & Rogers 1978).

2. Requirements for the dialog system of modeling

The first version of the interactive system was based on the following main requirements.

1. The dialog system should be simple in that the command language should be as close to natural as possible. Since the system is oriented toward nonspecialists in computer

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science, the leading role in the dialog should be played by the system itself. The user should only answer simple questions or select instructions from the menu.

2. An opportunity to control the modeling procedure should be provided; that is, one should have the opportunity to stop modeling, change the control variables, and then start modeling again.
3. Visual display of the modeling results should be provided. One should be able to obtain tables and graphs (on graphic display, printer, or plotter) during the modeling.
4. The system should provide opportunities f or flexible scenario setting. For demographic and medical demographic models the opportunity to set scenarios for such variables as age-specific mortality, age-specific fertility, crude birth rates, transition intensities, etc., should be provided. The system should also provide the opportunity to set the functions in terms of tables, and contain some standard functional forms, such as exponential, linear, etc.
5. The system should enable the user to change the structure of the model or incorporate a new one from the class of discrete-time Markov processes. The opportunity to change dialog in accordance with the changes in model type should be provided.
6. The opportunity to easily transfer the model from one computer to another should be provided.

3. Description of the model

A detailed mathematical description of the multistate population dynamics is given by Rogers (Rogers 1975; Rogers 1980). It has been shown that the dynamic of the population can be described by the equation

$$K(t+h) = G(t)K(t)$$

where K characterizes the population according to age groups and different states at times t and $t+h$, h is the time interval as well as the age interval, and G is the growth matrix:

$$G = \begin{bmatrix} 0 & 0 & B(\alpha-h) & \cdots & B(\beta-h) & \cdots & 0 & 0 \\ S(0) & 0 & & & & & . & . \\ 0 & S(h) & & & & & . & . \\ . & . & & & & & . & . \\ . & . & & & & & . & . \\ . & . & & & & & . & . \\ 0 & 0 & & & & & S(z-h) & 0 \end{bmatrix}$$

The first row of matrix G consists of the matrices $B(x)$,

$$B(x) = \left(\frac{h}{4}\right) C\,[P(0)+I][F(x)+F(x+h)S(x)]$$

where $F(x)$ is the diagonal matrix for birth rates of people aged x to $x+h$ years old in different states. The P matrix contains the survival probabilities from age x until $x+h$. The entries under the main diagonal of the G matrix determine the survival coefficients,

$$S(x) = [I+P(x+h)]P(x)[I+P(x)]^{-1}$$

The transition probabilities are calculated in the same manner as for increment-decrement life tables. At first the observed coefficients are grouped into the matrix:

$$M(x) = \begin{bmatrix} [M_{d1}(x) + \sum_{j \neq 1} M_{j1}(x)] & -M_{12}(x) & \cdots & -M_{1n}(x) \\ -M_{21}(x) & [M_{d2}(x) + \sum_{j \neq 2} M_{j2}(x)] & & -M_{2n}(x) \\ \vdots & \vdots & & \vdots \\ -M_{n1}(x) & -M_{n2}(x) & & [M_{dn}(x) + \sum_{j \neq n} M_{jn}(x)] \end{bmatrix}$$

where $M_{id}(x)$ is the age-specific annual death rate in state i, and $M_{ij}(x)$ is the age-specific annual transition rate from state j to state i.

The probability matrix P is calculated as follows

$$P(x) = [I + \frac{h}{2}M(x)]^{-1}[I - \frac{h}{2}M(x)]$$

The C matrix determines the state in which newborns appear in connection with their parents' state. Thus, the rows of the C matrix represent the states of the newborns and the columns represent the states of the parents. If, say, $C(i,j) = 1$ then the parents are in state j and the children will appear in state i. The C matrix satisfies the usual probabilistic constraints: $C(i,j) \geq 0, \sum_j C(i,j) = 1$.

Just (Just 1983) has shown that to complete the female dominant two-sex model a diagonal matrix X^f has to be defined. Its elements are the ratios of males to females born by a woman in each state. Usually these ratios are identical. Thus

$$X^f = \begin{bmatrix} s_1^{-f} & \cdots & & 0 \\ \vdots & \ddots & & \vdots \\ & & s_j^{-f} & \\ & & & \ddots \\ 0 & \cdots & & s_n^{-f} \end{bmatrix}$$

where

$$s_j^{-f} = 1/[1 + (b_j^m / b_j^f)]$$

and b_j^m and b_j^f denote the number of male and female births. For the female projection the first row of the growth matrix is given by elements

$$B^f(x) = \left(\frac{h}{4}\right) C X^f [P^f(0) + I][F(X) + F(x+h) S^f(x)]$$

The superscript f indicates that the survivorship proportions and probabilities of female population are used. The projection of the male population is performed in two steps. First the total (male and female) population at exact age 0 is calculated by

$$K^1(0) = \sum_x \left[F(x) + F(x+h)S^f(x)\right]^t K^f(x)$$

$K^1(0)$ is now input to the projection of males. The male population in the first age group at time $t + h$ can easily be derived by means of

$$^{t+h}K(0)^m = CX^m[P^m(0) + I]K^1(0)$$

where the elements s_i^{-m} of X^m are $1 - s_j^{-f}$. The other age groups are carried forward by

$$^{t+h}K^m(x+h) = S^m(x)^t K^m(x)$$

For $h \le x \le n - h$, where n stands for the last age group.

4. The structure of the interactive system

The block scheme for the dialog system, which satisfies most of the numerated requirements, is represented in Figure 1. The user starts the system by typing the name of the loading module SPAT. The rest of the dialog with the system is continued in the menu mode. The job control block asks the user which of the blocks is to have control:

1. Initialization.
2. Modeling.
3. Scenario setting.
4. Result representation.

The user types the number and the respective block controls the system.

4.1. Model Initialization

During model initialization the file with the initial data is read. This file should be prepared in a particular form, described in the Appendix A.1 and A.2. The model initialization procedure is necessary in the following cases:

a. Before starting work with a model.
b. Before a new start of the modeling procedure (starting a new scenario, f or example).
c. When choosing a new type of model (medical demographic or demographic) or a new model (another country or region) without exiting the system.

4.2. Scenario Setting

The system provides flexible and convenient setting of the control variables. These variables, which determine the scenario, can be set as a table in the interactive mode, when some fixed time points correspond to the values of the scenario variables or as a function of time.

Any model's parameter or exogenous variable can be chosen as a scenario variable, since the scenario determines the number of given variables. During the modeling procedure the values of the scenario variables are calculated f or any time in the scenario block, based on

Figure 1. Structure of the dialog system.

information determined by the user in the block for scenario setting. If for some variable the scenario is not set, its value is specified as a default value (calculated from initial data) and is unchangeable during the process of modeling.

A scenario setting block allows the user to:

1. Set the scenario on fertility.
2. Set the scenario on mortality.
3. Set the scenario on migration or transitions between states.
4. Set the scenario by a variable name.
5. Save the scenario.
6. Read a scenario from the file.

4.2.1. Scenario Setting for Fertility, Mortality, and Migration

Scenarios on fertility and mortality are determined for one or several states (regions). The system asks the state of departure and the state of destination for setting transition scenarios.

The gross fertility (GRRN), mortality (GDRN), and migration (GMRN) rates are taken as scenario variables. In modes 1, 2, and 3 when the nonnegative values of GRRN, GDRN, and GMRN are set, only the area under the age-specific rates of fertility, mortality, and migration (RAIF, RAID, and RATM) changeable; the shape of the age-specific rates is unchangeable.

For negative values, GRRN, GDRN, and GMRN act as switches, which is discussed later.

The scenario variable can have up to 10 values. The time and the values are specified as follows:

T1	Y1
T2	Y2
T3	Y3

During simulation the values of the scenario variables in between the given points are calculated using linear interpolation.

If the variable is specified as a f unction of time, the values of the respective coefficients that determine this f unction are determined. Note that each new set ting of the values for some scenario variable cancels values already specified.

4.2.2. Setting a Scenario by the Variable Name

The system provides an opportunity for scenario setting according to the variable name. For this purpose, the user should have the list of the variable names (identifiers) (Appendix A.4). Let, for instance, the user know that the identifier of the variable fertility coefficient for the first region in the list of regions in the model is GRRN (l). Then, being in mode 4 one should type the name GRRN (l) and, following the dialog, type the desirable values.

In this case there is the opportunity to set age-specific fertility, mortality, and transition rates. Knowing the respective identifier one can determine the scenario value of the coefficient for given states and age groups. If at the same time the value of the scenario variable for a gross rate, say, fertility GRRN , is set positive, then the area under the curve RATF will change and will equal the new value, but the form of the curve will not change. If GRRN is negative, then it will no longer be a gross reproduction rate, but act as a switch.

In this case no normalization and age-specific coefficients will stay the same, except for those that the scenario has specified. The area under the age distribution RATF will change. Note that the initial values of gross rates are calculated according to initial patterns of fertility, mortality, and migration.

4.2.3. Using the Mode of Scenario Setting by the Variable Name for Model Debugging

When working with the model it is sometimes necessary to look at the current value of variables the representation of which is not provided in the program. The mode of scenario setting by the variable name can be used f or this purpose, since during scenario setting in this mode the current value of this variable is printed first. Then the user decides whether to leave the variable unchanged or set it to a new value. Thus, to use this mode f or model debugging, one needs to know only the identifiers of the variables, which are given in the Appendix A.4.

4.2.4. Saving the Scenario

Creation of the scenario can be time-consuming, especially if the number of control variables is high. Since one sometimes needs to work with the same scenario again, the scenario can be saved. The user should provide the name of the scenario in order to do this, and the information about the scenario will be written to a disk file.

4.2.5. Reading the Scenario from the File

To work with a scenario that has already been created by the user or has been saved from the dialog system, there is the opportunity to read the scenario from the file. For this purpose, the user types the name of the file where the scenario is written. The file with the scenario is prepared according to the following rules:

a. the string is read as a comment if the first character is ‘c’;

b. the scenario variable is defined as the following function:

c. $< variable\ name >= TABLE(t_1, Y_1, t_2, Y_2, \dots, t_n, Y_n)$

d. where, $t_1, t_2, \dots, t_n$ are time points, $Y_1, Y_2, \dots, Y_n$ are values of the scenario variable;

e. the string can be transferred at any place;

f. a few scenario variables can be defined in the file;

g. only one scenario can be defined in the file.

After the scenario has been read, the user can deal with it as if it had just been created: one can add the new variable values, change the values of the old variables, etc.

4.3. Modeling

The simulation is performed in the modeling block. Modeling can be done in several time intervals. When the system asks “ENTER TIME SPAN”, the last year of modeling should be specified by the user. If the modeling procedure is started after the model initialization, then the time from the file used for initialization is taken as the initial time for the modeling interval. The modeling step coincides with the width of the age group. The modeling interval can consist of one or several steps.

During the modeling procedure the user has the following opportunities:

1. After completing the modeling process for the first time interval, one can continue modeling. For this purpose one should specify the end point of the new time interval. The end point of the previous time interval is considered as the initial point for a new interval of modeling.
2. One can represent the results of modeling after each specified modeling interval (dumping).
3. One can obtain result representation after each step of the modeling process.
4. One can change the values of the scenario variables and introduce new scenario variables.
5. One can stop modeling and start modeling again with a new model without exiting the dialog system.

4.4. Representation of Modeling Results

A representation block realizes the output of the produced results during the process of modeling (printing data during the run), as well as after completion of the modeling interval (dumping data).

During the modeling process information is represented in terms of tables and is written into the file associated with unit number 2 after each step (not the modeling interval). The list of tables is given in the menu. When dumping data, the result appears on the screen.

In order to achieve more independence from the available hardware environment (the size of the terminal screen or the width of the printer paper), a special table generator was developed. This helps to easily adapt the representation form for the results of modeling to the particular type and configuration of the computer. It also allows deletion of constraints related to the number of states and age groups in the model, which usually produce problems in representation of the results.

After completing the modeling procedure the results can be represented as:

1. Current values of the demographical variables in the form of tables.
2. Pie charts of the population structure at the current time.
3. A histogram of the age-specific population structure in each state (group) at the current time.
4. The population size in each state (group) starting from the initial time of modeling until the current year.
5. A new version of the system will include graphic representation of the population as a function of time and age using a three-dimensional plot.

The graphic information can be represented either by graphic display or plotter.

5. Realization

The dialog system was created f or use on the VAX 11/780. However, at each stage of its design, efforts were developed to make the system as machine independent as possible. The programming language used is FORTRAN 77, which minimizes the effort required to transfer this system to another computer.

Programs for the graphic representation of results are machine-dependent. For instance, IIASA uses the NEWPLOT system. During modeling the results are written in some auxilliary data file. The call to the NEWPLOT comes from the pro grams of the dialog systems written in FORTRAN. The NEWPLOT system uses a command file, which should be prepared beforehand, reads the data from the auxilliary data file, and plots the respective graphs. Control is then transferred back to the dialog system. Thus, the user should create the special command file for the NEWPLOT system, which then starts execution from the dialog system. In the new version of the dialog system, formation of the command file for the NEWPLOT system is realized automatically from the main system. The generalized version of the system, which takes into account sex composition of the population, is now being developed for PCs.

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Simulation of Multiregional Population Change: An Application to the German Democratic Republic[1]

Sergei Scherbov and Hartmut Usbeck

1. Introduction

This paper describes the application of the multiregional population projection simulation package available at IIASA[2] 1, to the German Democratic Republic (GDR). It is a continuation of previous work on migration and settlement in the GDR, which was one of the comparative studies of recent migration patterns and spatial population dynamics in all of IIASA's 17 National Member Organization countries (Mohs 1980). In these studies, all of which used a common computer program (Willekens & Rogers 1978), the multiregional population projections were based on constant rates of fertility, mortality, and migration. The way these three components can be expected to change the population distribution, growth, and age composition in the future is important for planning purposes. In this paper six scenarios of changes in fertility, mortality, and migration patterns are described, and the impact of these changes on regional population development is simulated.

The study begins with a short description of the methodological background and the main contents of the simulation package. In the second section a review is given of the current pattern of spatial population development in the GDR. The third section deals with the application of the simulation model for the GDR, and the paper ends with some conclusions and suggestions for further use of the model.

2. Possibilities of the simulation model computer package

Recent developments in the field of demography have made it possible to study the interregional migrations that take place between human settlement systems. A valuable contribution to these analyses was made by Rogers (1975), who extended the standard demographic life table to include multiregional populations. Further elaboration of the multiregional computer package for population projections (Willekens & Rogers 1978) allowed researchers in each IIASA country to study spatial population systems more deeply.

Computational analyses of the alternatives of population growth in the GDR, presented in this paper, were done with the help of a simulation model – an extension of the multiregional population projection model – which allows for the study of the impact of different demographic scenario variables on the population system, including the impact of international migration. Other scenario variables describe regional fertility, mortality, and origin-destination migration.

There are two types of variables in the simulation model. With the first, the sets of age-specific fertility, mortality, and migration rates can be changed. With the second, only the area under the age-specific curve is affected, but the shape of the curve remains unchanged. For fertility, then, the gross reproduction rate (GRR) is used since it is calculated by summarizing age-specific rates over all ages, and in the case of data given for 5-year age

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[2] The work on the simulation package was initiated by IIASA and continued by F. Willekens and R. Ramachandran at Vrije Universiteit, Brussels.

intervals, it is multiplied by 5. For mortality and migration the gross death rate and gross migration rate (GMR), which are calculated in the same way as the GRR, are used.

Changes in scenario variables may be instantaneous or may be introduced as linear functions of time.

The necessary data for the simulation model are for an initial year. These data are very close to those required for the projection model but also include the number of in- and emigrants by age and region when international migration (an open population) is considered. Scenario variables can be specified interactively, during the simulation run, as well as prepared in advance and saved in a data file. Examples of initial data and scenario specifications are presented in the Appendix.

It should be mentioned that the simulation model deals with a population not disaggregated by sex; all demographic variables such as fertility, mortality, and migration, therefore, take the total population into account. In the case of the GDR the population system is regarded as being closed.

3. Current patterns of spatial population development

Patterns of spatial population development are closely connected with the development of the territorial structure, the national economy, and the population policy of a country. In this section only a brief review of this background can be given (for further details, see Ludemann & Heinzmann 1978; and Mohs 1980). The territory of the GDR contains 108,000 km^2 with about 16.7 million inhabitants. In 1980 the divisions were 15 administrative districts (Bezirke), including Berlin as the capital, with 219 counties (Kreise) and 7,553 communities (Gemeinden). The GDR is a highly industrialized and urbanized country with more than 75 percent of the population being urban. The historical economic development pattern has produced sharp regional contrasts between the southern part, which has a high level of industrialization and population density, and the more agrarian northern part. Under the postwar socialistic conditions, however, these discrepancies have been reduced. The industrialization of the former agrarian regions has affected an evident development of material and cultural living conditions. This industrialization changed the regional population distribution, primarily because of the growing migration flows to the new industrial centers during the 1950s and 1960s. During the 1970s, this interregional migration shifted to shorter distance, local migration. At present the share of migration between districts, between counties within districts, and between communities within counties is nearly the same.

This analysis of current spatial population distribution patterns is based on observed 1975 characteristics. The data were provided by the Directorate of Statistics of the GDR, the central statistical bureau of the government, and are available at IIASA.

3.1 Regional Aggregation

The initial data were calculated for the 15 administrative districts. A regional data aggregation was necessary because of computing technicalities, planning constraints, and comparability with the former migration and settlement study (Mohs 1980).

Thus the 15 districts were aggregated into five regions, which are also used by the State Planning Commission for long term planning. These are:

1. The *North region*, including the districts of Restock, Schwerin, and Neubrandenburg
2. *Berlin*, capital of the GDR

3. The *Southwest region*, including the districts of Erfurt, Gera, and Suhl
4. The *South region*, including the districts of Halle, Leipzig, Dresden, and Karl-Marx-Stadt
5. The *Middle region*, including the districts of Magdeburg, Potsdam, Frankfurt, and Cottbus

The North region is more agricultural in structure than the others, although some important industrial centers have developed in the past. Berlin with its surroundings and the South region are agglomeration areas because of their density of population, cities, infrastructure, and industry. The Southwest and the Middle regions show a mixed economic structure, with the Cottbus district being the prime location of energy production in the GDR and Hagdeburg, Erfurt, Gera, and Frankfurt being important locations of processing industries.

3.2 Components of Multiregional Population Development

Fertility

In 1975, the base year of this study, the total population of the GDR was about 16,820,000. After a relatively constant period of a nearly zero growth rate during the 1960s, the population of the GDR decreased. The main reason was the decline in the fertility rate, brought about by the changing age structure of the population, the legalization of abortion in 1972, and a broad marketing of contraceptives. The lowest level of this development was reached in the middle of the 1970s (Table 1), a fact that must be considered in this study.

Since 1976, the total number of births, and with that fertility rates, have greatly increased, largely as a result of population and social policy measures. The regional differences in fertility, especially between the North and South regions, have diminished during the last decades (Table 2). The observed population characteristics and age-specific rates of the five regions in 1 975 are shown in Appendixes A1 and A2. The gross reproduction rate has the highest level in the Berlin and North regions (0.796, 0.794, respectively) and the lowest in the South region (0.736).

Figure 1 shows the age-specific fertility rates for the five regions. Above-average values can be seen for the North region in the first childbearing age group (15-19 years) and also in the 20-24-year age group. Berlin's shift to a higher age of childbearing is also evident, with

Table 1. Number of births and total fertility rates (TFR) in the GDR during the 1970s.

Year	Births	TFR
1970	236,929	2,192.5
1971	234,870	2,131.0
1972	200,443	1,786.0
1973	180,336	1,576.8
1974	179,127	1,539.7
1975	181,798	1,541.7
1976	195,483	1,636.8
1977	223,152	1,850.6
1978	232,151	1,899.0
1979	235,233	1,894.6
1980	245,132	-

Source: Statistical Yearbook of the GDR (1981).

Table 2. Fertility changes in the districts of the GDR.

District/Region	Total fertility rate 1964	 1971	 1974	 1979
NORTH				
Rostock	2.854	2.299	1.670	2.039
Schwerin	2.980	2.321	1.650	2.003
Neubrandenburg	3.175	2.367	1.658	2.072
Berlin	2.319	1.997	1.554	1.994
SOUTHWEST				
Erfurt	2.642	2.237	1.569	1.875
Gera	2.445	2.118	1.586	1.855
Suhl	2.546	2.218	1.554	1.824
SOUTH				
Halle	2.474	2.172	1.464	1.813
Leipzig	2.325	2.033	1.442	1.800
Dresden	2.433	2.133	1.618	2.013
Karl-Marx-Stadt	2.222	1.961	1.416	1.792
MIDDLE				
Frankfurt	2.819	2.203	1.579	1.924
Cottbus	2.769	2.351	1.641	2.008
Potsdam	2.668	2.146	1.487	1.808
Magdeburg	2.615	2.226	1.507	1.791
GDR	2.542	2.152	1.540	1.895

Source: Population Statistical Yearbook of the GDR (1966; 1973; 1976), Statistical Yearbook of the GDR (1981).

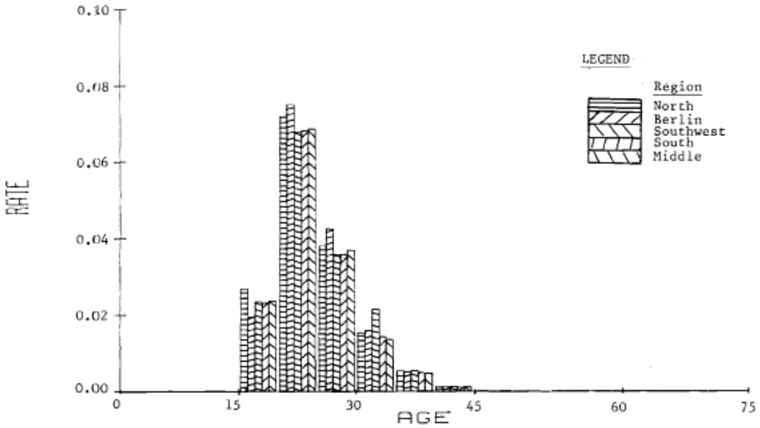

Figure 1. Age-specific fertility rates for five regions of the GDR, 1975.

the lowest value being in the first age group and the highest values in the second and third. The other regions show a similar behavior except for the Southwest region, which has an above-average value in the 30-34-year age group.

Mortality

Aggregate levels of mortality are determined to a high degree by the age structure of the population. The crude death rates have been nearly stable over the last two decades (1965, 13.5; 1970, 14.1; 1980, 14.2), although the age-specific rates, especially in the lower and middle age groups, have diminished. In the GDR one can find a very low death rate in the 0-1-year age group, and there exist only small regional differences in mortality levels among the five regions (Appendix A2).

The life expectancy of the 0-1-year age group has increased from 71-74 years during the period 1960-1975 for females and from 66-69 years for males. The average for the entire GDR population was 71.74 years in 1975 with a regional differentiation of 0.7 years. The increase of life expectancy is primarily a result of the considerable decline in infant mortality and improved living conditions in all regions.

Migration

Total migration has declined markedly during the last two decades in the GDR. Figure 2 shows the characteristic trends of migration flows between districts in the period 1953-1972. The following districts had a constant migration loss: Schwerin and Neubrandenburg (North Region), Karl-Marx-Stadt and Halle (South region), and Magdeburg (Middle region). On the other hand there has been growth due to migration in the Potsdam, Frankfurt, and Cottbus districts (Middle region) and in the Rostock district (North region) as well as

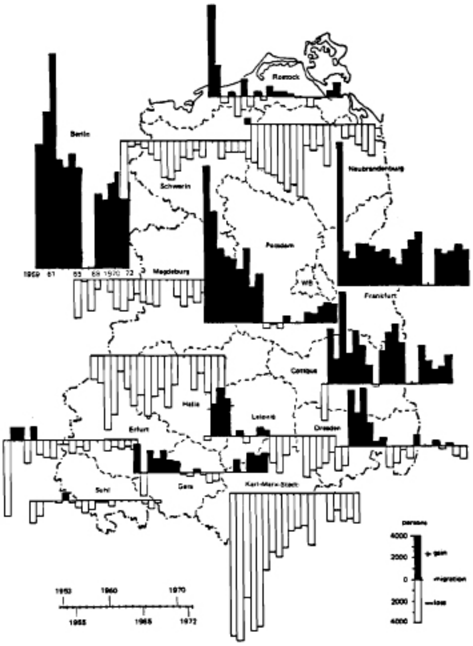

Figure 2. The evolution of migration between the districts of the GDR (all persons) during the period 1953-1972. Migration to Berlin is not included for the period 1 953-1 958.

Source: Bose (1975, Appendix).

Table 3. Number of migrants between regions (1975).

To/From	North	Berlin	Southwest	South	Middle	Arrivals
North	0	1,021	1,670	5,473	5,511	13,675
Berlin	2,897	0	1,790	5,655	9,192	19,534
Southwest	1,929	592	0	9,003	3,210	14,734
South	4,228	1,647	6,655	0	10,071	22,601
Middle	6,773	4,408	3,375	15,069	0	29,265
Departures	15,827	7,308	13,490	35,200	27,984	99,809

Table 4. Crude rates of outmigration for the five regions, 1975.

	Crude rate of outmigration				
To/From	North	Berlin	Southwest	South	Middle
North	0.	0.000930	0.000660	0.000767	0.001387
Berlin	0.001389	0.	0.000708	0.000793	0.002314
Southwest	0.000925	0.000539	0.	0.001262	0.000808
South	0.002027	0.001500	0.002631	0.	0.002535
Middle	0.003248	0.003686	0.001334	0.002112	0.
Total	0.007589	0.006655	0.005332	0.004934	0.007045

in Berlin, which has had the highest migration gain. It is evident that there is no strong relation between the economic structure of a region and migration balance. Table 3 shows migration flows between the five regions in the 1975 base year.

In 1975 Berlin, the Middle region, and the Southwest region had a migration gain, whereas the South and the North regions had a migration loss. The analysis of the observed outmigration rates with regard to the crude rates (Table 4) and also to the gross rates (Appendix A2) reflects on the one hand the demonstrated regional differences in migration flows and on the other hand the differences in the general spatial mobility of the population. One can find the highest value in the North region and the lowest value in the South region.

The age profile of the migrants is similar in all regions, with the highest values being in the 15-29-year age groups. This is mainly the well-known young family migration with children (relatively high values in the 0-4 age group) but also migration because of vocational training (15-20 years).

It should be mentioned that migration between the five regions reflects only a small share of the total migration. The main migration flows occur inside districts and counties and are mainly oriented to the district- and county-towns and to other important industrial centers. These short-distance flows influence, to an increasing degree the redistribution of the population to concentrated areas (for further details see Neumann 1978; and Usbeck 1982).

Age Structure of the Population

As previously mentioned by Mohs (1980), for the GDR analysis it was necessary to adjust the age group structure, which is used in the official statistics of the GDR, to 5-year age groups. In the Statistical Yearbook, the age groups are 0-1, 1-3, 3-6, 6-10, 10-15, 1 5-18, 18-21, and 21-25, followed by the 5-year age groups 25-30, and so on. These age groups were chosen for economic reasons, which are explained by Mohs (1980). A description of the adjustment procedure used is contained in Appendix A of that study.

For economic planning, a differentiation of the population in the pre-labor force age, labor force age, and post-labor force age is important. In the GDR these main age groups are the following:

Pre-labor force age - 0-15 years
Labor force age - 15-60 years (female)
15-65 years (male)
Post-labor force age - more than 60 or 65 years

Table 5 demonstrates the changes in the percentage distribution between these age groups during the last two decades.

There was a remarkable decline in the labor force age during the 1960s. Since the middle of the 1970s, there has been an increase in this age group, a result of the higher number of people who were born in the second half of the 1950s and the early 1960s and are now coming into the labor force age. This development will reverse after the mid-1980s. Table 5 reflects the unfavorable age structure of the GDR population because of one of the highest shares of 65 years and older persons of the world and a mean age in 1975 of 37 years.

Significant regional differences exist in the age structure of the population (Table 6). A detailed age composition by 5-year age groups is given in Figure 3.

The high share of the population in the post-labor force ages and the below-average share of the other two age groups in the South region are particularly evident, accentuating the contrast that exists in the North region. There are difficult problems in solving the shortage of manpower in the highly industrialized South region, which has many employment possibilities. Mohs (1980) points out that a planned production policy must be accompanied by a planned, temporary inmigration of people to the South. In the following six scenarios fertility, mortality, and migration rate alternatives will be simulated in order to show the reorientation of migration necessary to change the present situation.

Table 5. Age structure of the population of the GDR (in percent).

Year	Pre-labor force age	Labor force age	Post-labor force age
1960	21.0	61.3	17.6
1970	22.6	57.9	19.5
1975	20.6	59.7	19.6
1977	19.7	61.4	18.9
1980	18.9	63.2	17.9

Source: Statistical Yearbook of the GDR (1981).

Table 6. Age structure of the population in the GDR by region, 1 975 (in percent).[a]

	Region					
Age group	Total	North	Berlin	Southwest	South	Middle
0-14	21.34	23.96	21.30	21.56	19.96	22.36
15-64	62.35	62.52	62.55	62.55	62.10	62.35
65+	16.29	13.53	16.14	15.57	17.94	15.29
Mean age (years)	37.03	34.56	37.12	36.69	38.36	36.15

[a] The deviation from Table 5 results from different age group boundaries. For this study, the age groups of Table 6 were used.

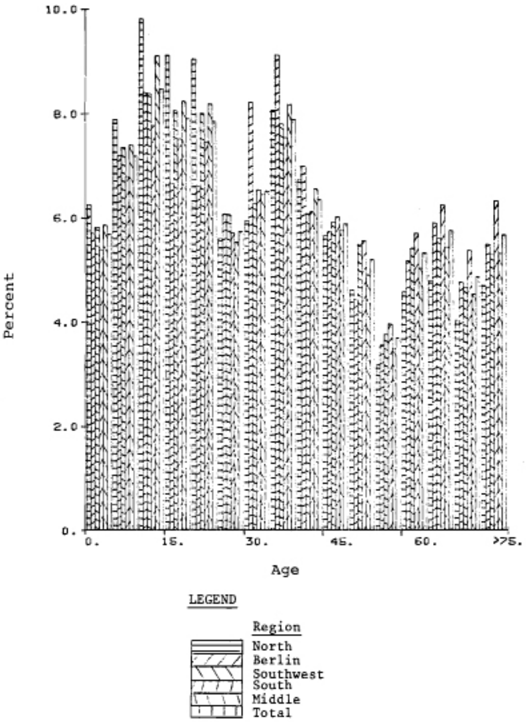

Figure 3. Population age structure of the GDR, 1 975.

4. Multiregional population projections with different scenarios

The projections carried out in this study are for 55 years – 1975-2030 – for the total population of the GDR by age. (Sexdistribution data were not available.)

4.1 Scenarios

The following multiregional population projections are made with changing rates of fertility, mortality, and migration for the total GDR population and for the five regions:

Base run:

Fertility	-	stable rates
Mortality	-	stable rates
Migration	-	stable rates

Scenario 1:

Fertility	-	increasing rates until 1980 and then stable
Mortality	-	stable rates
Migration	-	stable rates

Scenario 2:

Fertility	-	stable rates

Mortality - declining rates until 2030
Migration - stable rates

Scenario 3:

Fertility - stable rates
Mortality - stable rates
Migration - 1. declining gross migraproduction rates in all regions until 2000 and then stable
2. stable inmigration rates to Berlin

Scenario 4:

Fertility - increasing rates until 1 980 and then stable
Mortality - declining rates until 2000 and then stable
Migration - stable rates

Scenario 5:

Fertility - increasing rates until 1980 and then stable
Mortality - decreasing rates until 2030
Migration - 1. stable inmigration rates to Berlin until 1 990 and then decreasing rates
2. increasing inmigration rates to the South region since 1985
3. declining gross migraproduction rates in all regions until 2000 and then stable

Scenario 6:

Fertility - increasing rates until 1 980 in the North, Berlin, and Southwest regions; increasing rates until 1 990 in the South and Middle regions
Mortality - decreasing rates until 2030
Migration - 1. stable inmigration rates to Berlin until 1 990 and then decreasing rates
2. increasing inmigration rates to the South region since 1 985 until 2000 and then stable
3. decreasing outmigration rates from the South since 1 985 until 2000

4.2 Analysis and Interpretation

In the following, the results of the base run and of the six scenarios will be analyzed and interpreted with special attention given to population development until the year 2000 and in the second half of the projection period, focusing on the population development of the base run and scenarios 5 and 6. The reasons for this are:

1. Stable rates (base run) of the components of population change provide insight into the course of population development.
2. Scenarios 5 and 6 assume considerable changes in the migration patterns of Berlin and the South regions. Thus population changes in Berlin, the present capital and the main center of investment activity, as well as in the South region, the economic center of the country, are of high political and economic importance.

Base Run

In the base run a development of the multiregional population structure of the GDR with 1975 stable rates is projected. This projection was already made by Mohs (1980), but unfortunately in his study an important computing error was made, which greatly influenced the results of the long-term projection. There was a shift of fertility rates in the Berlin, Southwest, and South regions by one age group (Mohs 1980, p.47–49,51). Because this mistake directly influenced such values as the gross reproduction rate and the mean age of childbearing as well as migration in the population projection, the base run had to be repeated for this analysis.

In multiregional population projections that use stable rates, the base year structural patterns influence the demographic development during the whole projection period. The situation in 1975 is described in section 3.

With the assumption of stable rates the total population of the GDR is expected to decline by -6.5 percent to the year 2000 and by -24.0 percent to the end of the projection period (Table 7). According to this development, the regional shares of the total population will change in the following way (Table 8).

From this base-run scenario it is evident that Berlin will be the main “winner” and the South region the main “loser” of this change. Since the rates of the components of change are stable, the changing age structure will mainly influence the regional differentiation. This is reflected by the patterns of births and deaths during the projection period (Figures 4 and 5). After a low increase to 1985, caused by the higher number of persons in the childbearing age groups, the number of births declines markedly, especially in the South region. This is an expression of the high percentage of persons in the older age groups. The only exception is Berlin, which has a nearly stable number of births because of the high inmigration of younger people.

The total number of deaths decreases until 1995 in all regions because the rates refer to persons born in the period between the two world wars who suffered high losses during World War II and therefore make up age groups that now have a minimum number of

Table 7. Total population change by regions, 1 975-2030, base run.

	Total population (in thousands)			Absolute change (in thousands)		Change (in percent)	
Region	1975	2000	2030	1975-2000	1975-2030	1975-2000	1975-2030
North	2,085	2,051	1,710	-34	-375	-1.7	-18.0
Berlin	1,098	1,337	1,359	+239	+261	+21.8	+23.8
Southwest	2,530	2,433	2,030	-97	-500	-3.9	-19.8
South	7,135	6,107	4,571	-1,028	-2,564	-14.5	-35.9
Middle	3,972	3,802	3,128	-170	-844	-4.3	-21.3
GDR	16,820	15,730	12,798	-1,090	-4,022	-6.5	-24.0

Table 8. Regional shares of the total population, 1975-2030, base run (in percent).

Year	North	Berlin	Southwest	South	Middle
1975	12.4	6.6	15.0	42.4	23.6
2000	13.0	8.5	15.1	38.8	24.2
2030	13.4	10.6	15.9	35.7	24.4

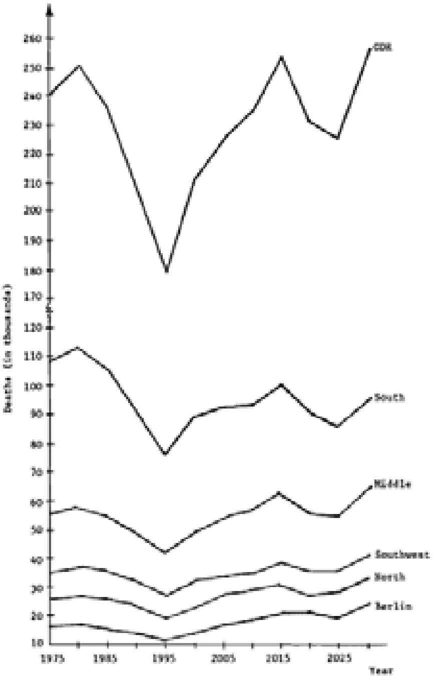

Figure 4. Evolution of total deaths (base run).

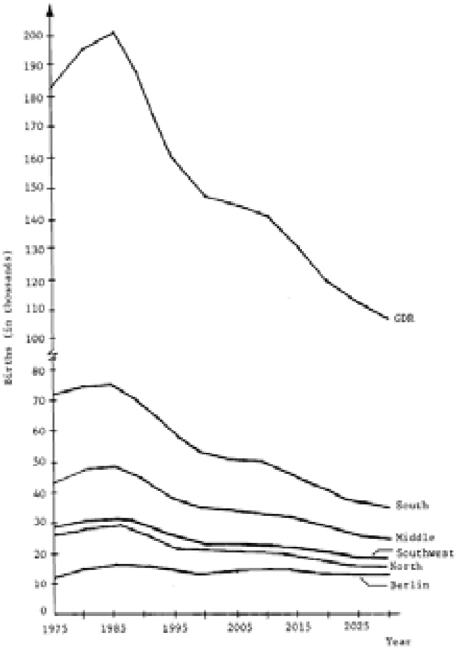

Figure 5. Evolution of total births (base run).

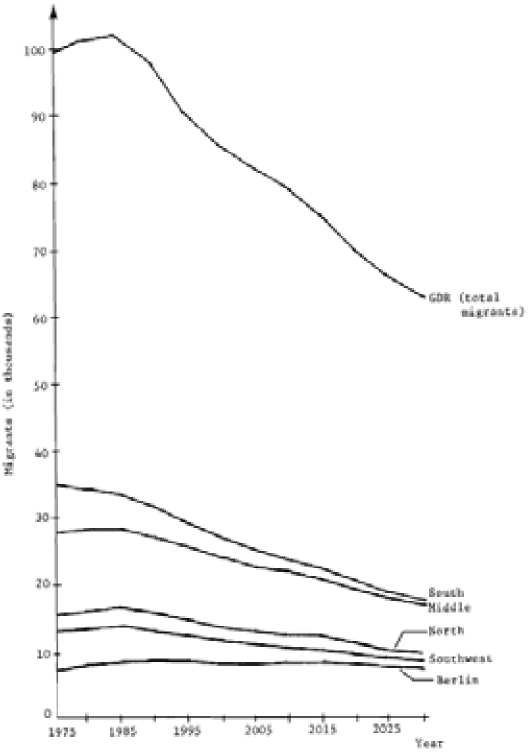

Figure 6. Evolution of the number of outmigrants (base run).

persons. The following increase in the number of deaths, along with the decrease of births, leads to the fast population decline in the second half of the projection period.

In the base run, the mean age of the total GDR population is expected to increase by seven years by 2030 (1975, 37.03 years; 2030, 44.14 years) with the lowest growth being in Berlin (+4 years). This higher mean age will also influence the volume of migration. There will be a decrease in the total number of migrants from about 100,000 (1975) to nearly 63,000 (2030) (Figure 6). The decrease is highest in the South region, which has the oldest population; outmigration from Berlin tends to be stable.

The change of proportions between the labor force age groups and the pre- and post-labor force age groups is important for economic planning. Despite the continued decline of total population the share of persons in the labor force age group will be increasing until 1 995 and then a large drop will occur, according to the base run. The regional shares of the three main age groups are given in Table 9.

The low share of the labor force age group especially in the highly industrialized South region will require a changing manpower and population distribution policy, which should include a policy for improving the regional conditions necessary for a higher natural increase.

The resulting age structure of population for the year 2030 if illustrated as a population pyramid would show a form similar to a rectangle, with growing population shares connected with older age groups (Figures 7-1 2).The present population distribution and growth rate

Table 9. Percentage of population in the three main age groups by region, 1975-2030, base run.

		Year		
Region		1975	2000	2030
NORTH	PrA	24.0	17.5	14.2
	LA	62.5	69.9	63.5
	PoA	13.5	12.6	22.3
BERLIN	PrA	21.3	17.7	15.0
	LA	62.6	71.8	66.7
	PoA	16.1	10.5	18.3
SOUTH-WEST	PrA	21.6	16.8	14.1
	LA	62.9	69.4	63.9
	PoA	15.5	13.8	22.0
SOUTH	PrA	20.0	15.2	12.7
	LA	62.1	68.9	62.8
	PoA	17.9	15.9	24.5
MIDDLE	PrA	22.4	16.3	13.2
	LA	62.3	70.2	63.6
	PoA	15.3	13.5	23.2
TOTAL	PrA	21.3	16.2	13.5
	LA	62.4	69.7	63.7
	PoA	16.3	14.1	22.8

PrA - Pre-labor force age; LA - Labor force age; PoA - Post-labor force age

is mainly reflected in the older age groups, thus underlying the idea that if one projects the population with a constant growth rate for a long time period it will become a stable population (Willekens & Rogers 1978).

The results of the base run are important to see what will happen in the future if the observed rates remain stable. During the second half of the 1970s, however, a large rise in the fertility rate in all regions took place; thus the projected values of the base run are

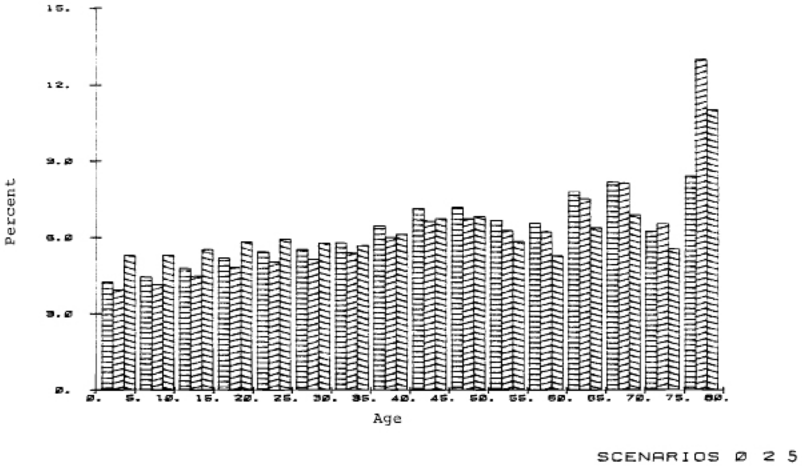

Figure 7. Age structure of the total population of the GDR, 2030.

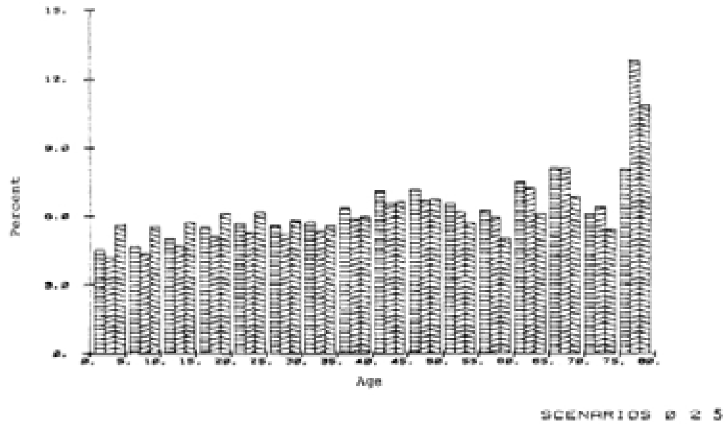

Figure 8. Population age structure of the North region, 2030.

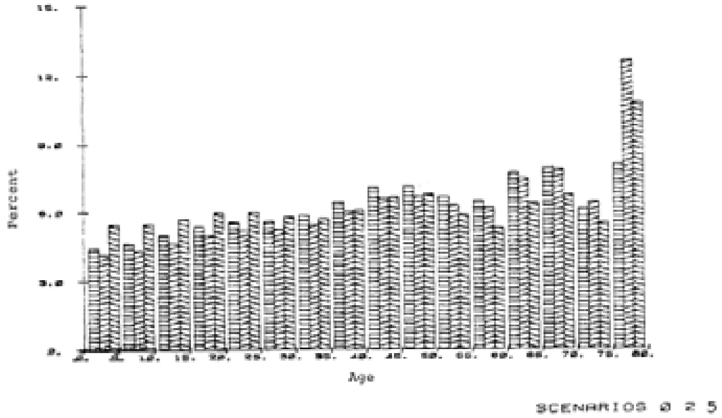

Figure 9. Population age structure of the Berlin region, 2030.

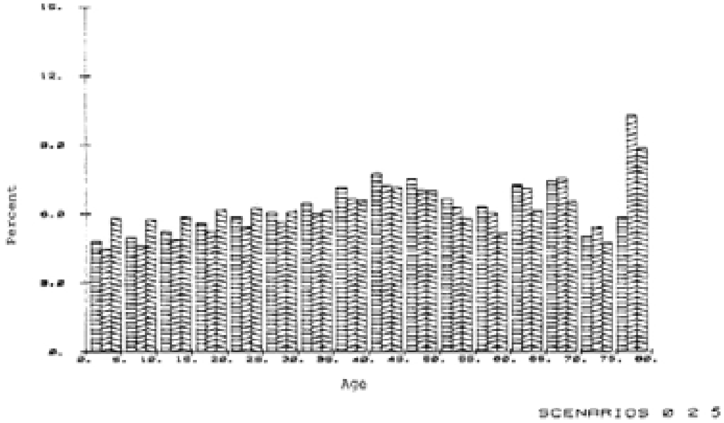

Figure 10. Population age structure of the Southwest region, 2030.

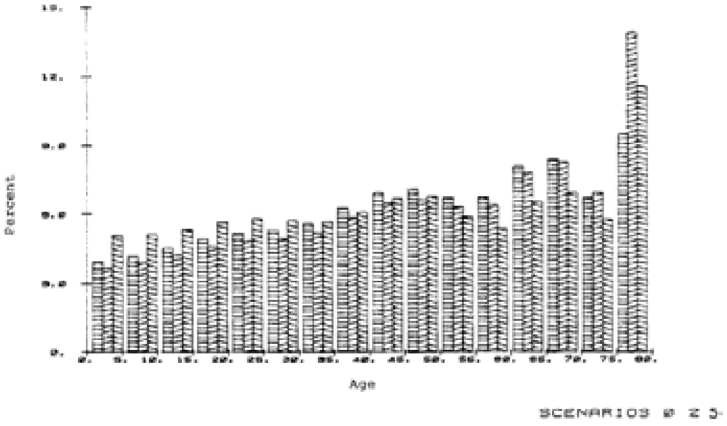

Figure 11. Population age structure of the South region, 2030.

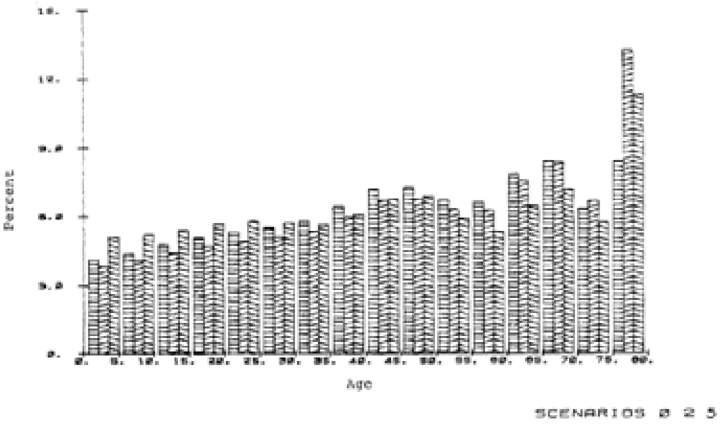

Figure 12. Population age structure of the Middle region, 2030.

underestimated. This will be seen later in the comparison of the projected and real values for 1 980 between all scenarios.

Scenario 1

Here the assumption is that the regional fertility rates will increase to the average of the country in 1980 and then will remain constant during the whole projection period. There will be no change in the mortality and migration rates. The assumption that fertility rates will be nearly stable after the increase in the second half of the 1970s also made in the population projection of the State Planning Commission (Stempell & Weber 1978).

The increase of fertility rates leads to quite different results when compared with the base run. In Scenario 1 , to the year 2000 there is only a small decline of the total GDR population, but in the second half of the projection period it drops to a much lower figure than in the base run (Table 1 0). This sharp decrease can be explained also by the changing age structure (see above). The regional differentiation is lower, and except for the South region, all other regions are expected to have a population gain until 2000. The population

Table 10. Total population change by region, 1975-2030, Scenario 1.

	Total population (in thousands)			Absolute change (in thousands)		Change (in percent)	
Region	1975	2000	2030	1975-2000	1975-2030	1975-2000	1975-2030
North	2,085	2,172	2,083	+87	-2	+4 .2	-0.1
Berlin	1,098	1,416	1,681	+308	+583	+29.0	+53.1
Southwest	2,530	2,585	2,508	+55	-22	+2.2	-0.9
South	7,135	6,552	5,821	-583	-1314	-8.2	-18.4
Middle	3,972	4,083	3,969	+111	-3	+2.8	-0.1
GDR	16,820	16,809	16,063	-11	-757	-0.1	-4.6

Table 11. Mean age of the population by region, 1975-2030, scenario 1.

	Mean age		
Region	1975	2000	2030
North	34.56	36.78	39.72
Berlin	37.12	36.09	38.08
Southwest	36.69	37.59	39.60
South	38.36	38.90	40.43
Middle	36.15	37.43	39.78
Total	37.03	37.83	39.80

Table 12. Percentage of population in the three main age groups of the GDR population, 1 975-2030, scenario 1.

Age group	1975	2000	2030
Pre-labor force age	21.3	19.4	18.2
Labor force age	62.4	67.4	63.6
Post-labor force age	16.3	13.2	18.2

gain of Berlin is higher than in the base run because of the higher fertility rates and a higher number of inmigrants.

The mean age of population is expected to increase by about three years. The regional differences sharply decline (Table 11), but the mean age of Berlin's population will increase only by one year. Because of the continuous migration gain, the capital will have the lowest mean age at the end of the projection period.

In spite of a higher fertility rate, the share of persons in the pre-labor force age group is decreasing. As in the base run the percentage of persons in the labor force age group is expected to increase until the end of this century and then a large drop will occur. In connection with this, the share of the elderly population (post-labor force ages) can be expected to be higher than at the beginning of the period (Table 12).

Only the values for the South region are below average in the pre- and labor force ages and above average in the elderly group.

Scenario 2

Here a change of the gross death rate is assumed from 1.3 (1975) to 0.9 (2030) and rates of fertility and migration remain stable. Because of the stable fertility rates, scenario

Table 13. Total population change by region, 1975-2030, scenario 2.

	Population (in thousands)			Absolute change (in thousands)		Change (in percent)	
Region	1975	2000	2030	1975-2000	1975-2030	1975-2000	1975-2030
North	2,085	2,084	1,861	-1	-224	-0.05	-10.8
Berlin	1,098	1,359	1,476	+261	+378	+23.8	+34 .4
Southwest	2,530	2,474	2,197	-56	-333	-2.3	-13 .2
South	7,135	6,213	4,941	-922	-2194	-13.0	-30.8
Middle	3,972	3,867	3,412	-105	-560	-2.7	-14.1
Total	16,820	15,997	13,888	-823	-2932	-4.9	-17.4

Table 14. Mean age of population/life expectancy by region, 1975-2030, scenario 2.

	Mean age			Life expectancy		
Region	1975	2000	2030	1975	2000	2030
North	34.56	38.74	45.65	71.31	73.71	76.87
Berlin	37.12	38 .00	43.88	71.13	73.67	77 .12
Southwest	36.69	39.74	45.66	71.69	73.98	76.99
South	38.36	41.41	47.22	72 .01	74.18	76.98
Middle	36.15	39.85	46.58	71.39	73.77	76.91
Total	37.03	40.14	46.25	71.51	73.86	76.97

Table 15. Percentage of population in the three main age groups of the GDR, 1 975-2030, scenario 2.

Age group	1975	2000	2030
Pre-labor force age	21.3	16.0	12.6
Labor force age	62.4	68.8	59.8
Post-labor force age	16.3	15.2	27.7

2 generates a remarkable population loss in all regions except Berlin (Table 13). The lower death rates bring about a smaller population loss in all regions than in the base run, however.

The expected development causes an average shift of the mean age by nearly 10 years and of the life expectancy by more than 5 years (Table 14).

The age structure of the population, given in Figures 7-12 in comparison with the two other scenarios, shows for scenario 2 the lowest percentage values until the age group 45-50 years and the highest values in the age groups above 65 years. This results in a remarkable shift between the three main age groups during the projection period (Table 15).

The regional differentiation is similar to the base run.

Scenario 3

In this scenario fertility and mortality rates are expected to remain stable, as well as the inmigration rates to Berlin. This is based on the assumption that Berlin will continue to be the main center for investment activities in the future. On the other hand a trend from long distance migration to short distance migration has been evident in the past, and it is assumed that this tendency will also continue in the future. Thus the outmigration rates of all regions are expected to decline by 10 percent until the end of the projection period.

Table 16. Total population change by region, 1975-2030, scenario 3.

	Total population(in thousands)			Absolute change in thousands)		Change (in percent)	
Region	1975	2000	2030	1975-2000	1975-2030	1975-2000	1975-2030
North	2,085	1,996	1,558	-89	-527	-4.3	-25.3
Berlin	1,098	1,349	1,398	+251	+300	+22.9	+27.3
Southwest	2,530	2,430	2,022	-100	-508	-4.0	-20.1
South	7,135	6,113	4,582	-1022	-2553	-14.4	-35.8
Middle	3,972	3,842	3,235	-130	-737	-3.3	-18.6
Total	16,820	15,730	12,795	-1090	-4025	-6.5	-24.0

Table 17. Migration flows between the North, South, and Middle regions, 1975 and 2030, scenario 3.

To/From	1975			2030		
	North	South	Middle	North	South	Middle
North	-	5,473	5,511	-	2,512	317
South	4,228	-	10,071	2,167	-	5,875
Middle	6,773	15,069	-	3,572	7,010	-

Table 18. Mean age of the population by region, 1975-2030, scenario 3.

	Mean age		
Region	1975	2000	2030
North	34.56	38.53	44.07
Berlin	37.12	37.47	41.48
Southwest	36.69	39.24	43.59
South	38.36	40.90	45.23
Middle	36.15	39.24	44.12
Total	37 .03	39.64	44.14

Because fertility and mortality rates will remain stable, scenario 3 leads to a population loss for the whole country by more than 4 million people until 2030, as in the base run (Table 16).

With respect to the population development of the five regions, the North region has a higher population loss in scenario 3 than in the base run. With a general decline of the outmigration rates in all regions the net migration balance of the North region tends to be worse in comparison with the other regions. This is a result of the higher mobility of the younger population of the North region than of the South and Middle regions, which have an older population and the strongest migration ties with the North region (Table 17).

Migration change also influences the regional differences of the mean age of the population. It can be seen that the highest mean age increase is expected in the North region and the lowest in Berlin (Table 18), which results in a more equal regional mean age.

The composition of the three main age groups of scenario 3 is similar to that of the base run with a small shift to the older age groups in the North region.

Table 19. Total population change by region, 19752030, scenario 4.

	Total population (in thousands)			Absolute change (in thousands)		Change (in percent)	
Region	1975	2000	2030	1975-2000	1975-2030	1975-2000	1975-2030
North	2,085	2,232	2,220	+147	+135	+7.1	+6.5
Berlin	1,098	1,458	1,794	+360	+696	+32.8	+63.4
Southwest	2,530	2,661	2,656	+131	+126	+5.2	+5.0
South	7,135	6,734	6,133	-401	-1002	-5.7	-14.0
Middle	3,972	4,202	4,225	+230	+253	+5.8	+6.4
Total	16,820	17,287	17,029	+467	+209	+2.8	+1.2

Table 20. Mean age of the population by region, 1 975-2030, scenario 4.

	Mean age		
Region	1975	2000	2030
North	34.56	37.62	41.42
Berlin	37.12	36.99	39.86
Southwest	36.69	38.50	41.15
South	38.36	39.75	41.83
Middle	36.15	38.32	41.45
Total	37.03	38.70	41.37

Table 21. Percentage of population in the three main age groups of the GDR, 1975-2030, scenario 4.

Age group	1975	2000	2030
Pre-labor force age	21.3	19.0	17.4
Labor force age	62.4	66.0	61.1
Post-labor force age	16.3	15.0	21.5

Scenario 4

In scenario 4 fertility is expected to increase to a national average of 0.95 by 1980 in all regions and to be stable in the following period. It should be mentioned that this assumption takes into account the fertility rate of the South region, which was below the national average and those of the North and Berlin regions, which were above the national average. Thus the projected values for the South region might be overestimated.

With respect to mortality a decline of the gross death rate to 1.0 until 2000 is assumed, with the death rate remaining stable in the second half of the projection period. Migration rates remain stable throughout.

The decline of the death rate leads to an increase of the average life expectancy to 75.4 years for the whole country with only low regional differences.

According to this scenario, the GDR will have a low population growth after the year 1980 to a peak in 2015 of 17.6 million people, followed by a decline with the higher share of population being in the older age groups (Table 19).

In scenario 4, the South region shows the lowest population loss in comparison with all previous scenarios. Nevertheless, although the fertility increase is overestimated, the population loss is primarily a result of the high negative migration balance and the above-average share of the older population. This result emphasizes the necessity of a change in the population distribution policy that would benefit the South region in the future.

On the other hand the capital of Berlin will have a population gain by about 700,000 people, which is much more than the present population of Leipzig.

Although fertility is expected to increase, the replacement level will not be reached. Scenario 4 leads, together with a higher life expectancy (75.4 years), to an increase of the mean age but at a lower pace than in the previous scenarios. The regional differences are expected to diminish (Table 20).

The percentages of the three main age groups up to 2030 are given in Table 21. Although the fertility rate will be much higher in 2030 than in 1975, a continuous decrease of the share of children will take place in all regions. The principal evolution of the two other age groups is similar to the previous scenario.

Scenario 5

Scenario 5 includes changes in all components. The fertility rate is expected to increase by 20 percent until 1 980 and tends to be stable beyond that year. This assumption excludes the overestimation of the natural growth in regions with belowaverage fertility rates (South region). The death rate will decrease in the same way as in scenario 2.

With regard to migration the gross inmigration rates to Berlin are expected to be stable until 1 990 and then will decline by 20 percent from all regions until 2030. To diminish the population loss of the South, a 20 percent inmigration rate to this region from 1 985 to 2030 is assumed. In accordance with the change from long-distance to short-distance migration, a 20 percent decline of the gross migraproduction rate can be expected in the large regions by 2030. For Berlin the GMR is expected to be stable, because Berlin has strong interrelations with its hinterland, and the suburbanization process, which can actually be observed in its initial stage, might continue in the future.

The total population development shows nearly zero growth until 201 5 and then a decline (Figure 13). This decline results above all from the high number of persons in the oldest age groups, who were born in the two post-war decades. In this scenario the total population loss is higher than in scenario 4 because here the regional differentiation of natural increase was taken into account.

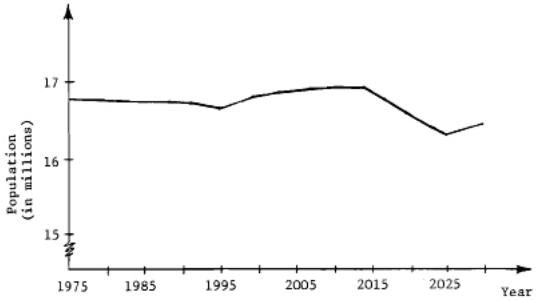

Figure 13. Development of the GDR population, 1975-2030, scenario 5.

Table 22. Total population change by region, 1975-2030, scenario 5.

	Total population (in thousands)			Absolute change (in thousands)		Change (in percent)	
Region	1975	2000	2030	1975-2000	1975-2030	1975-2000	1975-2030
North	2,085	2,194	2,184	+109	+99	+5.2	+4.7
Berlin	1,098	1,428	1,679	+330	+581	+30.1	+52.9
Southwest	2,530	2,597	2,543	+67	+13	+2.6	+0.5
South	7,135	6,524	5,982	-611	-1153	-8.6	-16.4
Middle	3,972	4,080	3,979	+108	+7	+2.7	+0.2
Total	16,820	06,823	16,370	+3	-450	+0.0	-2.7

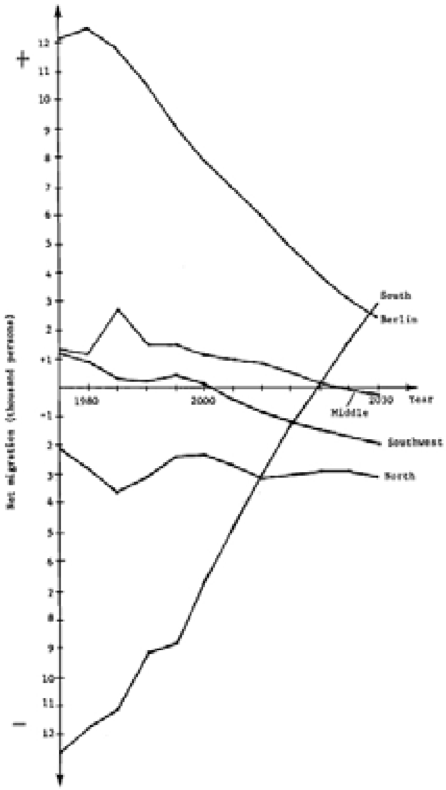

Figure 14. Change of net migration balance by region, 1975-2030, scenario 5.

The assumed change of migration patterns leads to a different population development of the regions (Table 22). Although an inmigration increase to the South region is assumed, a considerable population loss for this region is evident. It is higher than in scenario 4 with its stable migration rates. The main reason for this is the overestimation of fertility in this region in scenario 4. The changing migration patterns are illustrated in Figure 14. Although inmigration to the South region shows a continuous increase, it does not outweigh outmigration until 2020. In addition, natural increase never is positive during the entire projection period.

Table 23. Total population change by region, 1875-2030, scenario 6.

	Total population (in thousands)			Absolute change (in thousands)		Change (in percent)	
Region	1975	2000	2030	1975-2000	1975-2030	1975-2000	1975-2030
North	2,085	2,191	2,177	+106	+92	+5.1	+4.4
Berlin	1,098	1,421	1,663	+323	+565	+29.4	+51.4
Southwest	2,530	2,591	2,530	+61	±0	+2.4	±0
South	7,135	6,568	6,209	-567	-926	-7.9	-15.6
Middle	3,972	4,079	4,018	+107	+46	+2.6	+1.2
GDR	16,820	16,851	16,597	+31	-223	+0.2	-1.4

The migration gain of Berlin is expected to decrease continuously. At the end of the period it becomes smaller than the gain of the South region. Along with the favorable inmigration to the South region, scenario 5 projects a less favorable migration balance in all other regions. Nevertheless, the total population development of Berlin is positive because of natural increase. This holds true especially for the North region with its continuous negative net migration balance.

The regional population development in scenario 5 will lead to an increase of the mean age of population to 42.7 years on the average, with the highest value being in the South region (43.8 years) and the lowest in Berlin (40.8).

From these results the following conclusions can be drawn:

1. The assumed increase of inmigration to the South region leads to a positive net migration balance beginning in 2020. A considerable change in the South's labor force age group requires a more extensive redistribution of the population at an earlier stage.
2. The natural increase of the population in the South region has to be improved. This can be accomplished by higher investments in infrastructural sectors, which further improve living conditions and support an increase in the fertility rate.

Scenario 6

Based on the conclusions of scenario 5, the special aim of this scenario is to decrease the population loss of the South region. Therefore it is assumed that besides the general growth of the fertility rates until 1 980, a further growth will occur in the South and Middle regions, those with the lowest fertility rates, to equalize the regional fertility rates until 1990. The same assumption for mortality is used as in scenario 5. To improve the migration balance of the South region, the inmigration rates to the South from all regions should increase by 30 percent from 1985 to 2000 and then remain stable. On the other hand the outmigration rates from the South should decrease by 20 percent during the same period.

From Table 23 it can be seen that the population loss of the South region is comparatively lower in scenario 6 than in all other scenarios. Nevertheless the decrease of the total population of the GDR is a result of the population loss of the South region, because all other regions register a population gain.

The population loss of the South region is a result of both a long-term negative migration balance and negative natural increase rates. Despite a considerable increase in inmigration rates and a decrease in outmigration rates assumed in scenario 6 for the South region, a positive migration balance will not appear until the end of the projection period (Figure

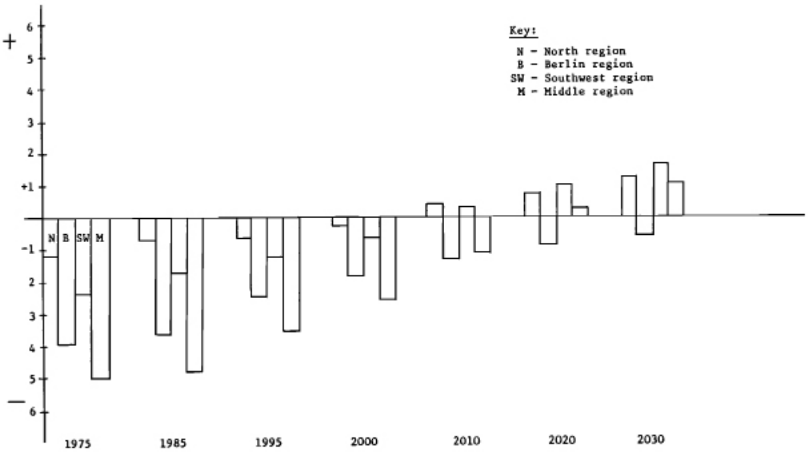

Figure 15. Net migration balance between the South region and all other regions, scenario 6.

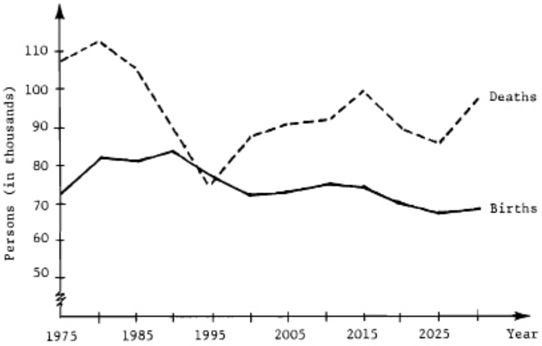

Figure 16. Births and deaths in the South region, 1975-2030 (in thousand persons), scenario 6.

Figure 17. Births and deaths in the Berlin region, 1975-2030 (in thousand persons), scenario 6.

Table 24. Mean age of population by region, 1 975-2030, scenario 6.

	Mean age		
Region	1975	2000	2030
North	34.56	37.32	42.11
Berlin	37.12	36.68	40.80
Southwest	36.69	38 .36	42.32
South	38.36	39.82	42.56
Middle	36.15	38.35	42.75
GDR	37.03	38 .65	42.33

Table 25. Percentage of the population in the three main age groups by region, 1975-2030, scenario 6.

	Region																	
	North			Berlin			Southwest			South			Middle			GDR		
Year	PrA	LA	PoA	PrA	LA	PoA	PrA	LA	PoA	PrA	LA	PoA	PrA	LA	PoA	PrA	LA	PoA
1975	24.0	62.5	13.5	21.3	62.6	16.1	21.6	62.9	15.5	20.0	62.1	17.9	22.4	62.3	15.3	21.3	62.4	16.3
2000	19.8	57.2	13.0	10.1	69.0	10.9	19.1	66.8	14.2	18.0	65.9	16.1	19.0	67.2	13 .8	18.8	66.8	14.4
2030	17.0	59.9	23.1	17.5	62.3	20.2	16.7	60.3	23.0	16.5	59.9	23.5	16.4	59.7	23.9	16.7	60.2	23.1

PrA - Pre-labor force age; LA - Labor force age; PoA - Post-labor force age

15). The natural increase will be negative during the whole projection period despite the initial increasing fertility rates (Figure 16).[3] On the contrary, the Berlin region has a positive migration balance until 2030 and a substantially favorable natural increase rate (Figure 17).

The increase in the mean age of the population is somewhat smaller than in scenario 5, which has more equality between regions (Table 24). The fast increase of the mean age in the second half of the projection period is connected with the changing age structure of the population. The post-war baby boom (those born before 1965), will come into the post-labor force age group in 2030. This large birth cohort reflects the changing proportions of the three main age groups (Table 25).

The share of persons in the labor force ages is greatest between 1985 and 1995. The Middle region has the least percentage of this main age group because of its strong migration connections to Berlin and the South region, whose inmigration rates are growing in this scenario. In general the change is similar to most of the other scenarios.

With respect to the main aim of scenario 6, the improvement of population development especially in the South region, the following conclusion can be drawn:

By increasing the fertility rate and considerably reorienting migration flows to benefit the South region, a lower population loss of this region can be reached in comparison with the previous scenarios. But since the population loss amounts to more than 900,000 persons before 2030, a stronger population redistribution policy would be necessary to solve the labor force problem in the future. This seems to be possible from the pure demographic/geographic point of view, because all other regions, especially Berlin, have an increasing population and a more favorable age structure (except the Middle region at the end of the period). It is urgent that this problem be solved, because despite a high percentage share

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[3] Note that the comparison of the total number of births and deaths can be done only far 5-year steps. The values for the intervening years may differ, but for the South region it should not change the general picture to a great extent.

Table 26. Comparison between the observed and projected values for 1980, for all scenarios.

	Regions					
	GDR	North	Berlin	Southwest	South	Middle
Observed population in 1980	16,739,538	2,100,594	1,152,529	2,529,009	6,981,660	3,975,746
Projected population by						
I. Base run	16,641,906	2,086,653	1,142,995	2,519,815	6,947,690	3,944,753
deviation in %	-0.60	-0.67	-0.87	-0.36	-0.49	-0.78
II. Scenario 1	16,762,373	2,099,871	1,149,479	2,536,284	7,000,616	3,976,123
deviation in %	+0.13	-0.05	-0.35	+0.25	+0.27	+0.01
III. Scenario 2	16,666,322	2,089,343	1,144,974	2,523,425	6,958,233	3,950,447
deviation in %	-0.45	-0.58	-0.61	-0.24	-0.34	-0.66
IV. Scenario 3	16,641,898	2,084,277	1,143,400	2,519,658	6,948,071	3,946,493
deviation in %	-0.59	-0.81	-0.87	-0.36	-0.49	-0.76
V. Scenario 4	16,803,198	2,104,488	1,152,867	2,542,383	7,017,596	3,985,865
deviation in %	+0.37	+0.14	+0.01	+0.51	+0.52	+0.25
VI. Scenario 5	16,758,101	2,101,165	1,151,352	2,536,753	6,993,741	3,975,089
deviation in %	+0.10	+0.02	-0.18	+0.31	+0.17	-0.02
VII. Scenario 6	same values as in scenario 5					

of the labor force in the year 2000 the total number of persons in this age group will be continuously decreasing from 4.4 million (1975) to 4.3 million (2000) and 3.7 million (2030). The chances of increasing fertility above the projected level seem smaller than reorienting the migration flows to the benefit of the South region, more so even than assumed in this scenario. Such a policy is connected with many economic, environmental, and individual problems of the migrants that are too numerous to be discussed in this paper. That a planned economy has all possibilities for such a policy has been demonstrated in the GDR in the past by many examples (see Mohs 1980).

General Assessment of the Scenarios and Their Results

The base run and the six scenarios treated in this paper are based on different changes in the components of population development, i.e., fertility, mortality, and migration. The observed initial data are from 1975 and for a first assessment of all scenario results it is possible to compare the projected values for 1980 with observed data for this time (Table 26).

It is evident that the projected values of scenarios 1, 5, and 6 have the best fit with the observed values both for the whole country and for the regions. In the base run and scenarios 2 and 3 an underestimation can be observed, because they deal with the low fertility rates of 1975 over the whole period. On the other hand scenario 4 shows an overestimation, because fertility is expected to increase to a unit level of 0.95 in 1985, which is true for the North and Berlin regions but is too high for the other regions.

Comparison with the values for 1 980 shows that the last two scenarios and the base run give the closest fit to possible development under unchanged conditions. This has been done in the previous sections.

In all scenarios that assume increasing fertility rates, these rates remained stable after 1980 (except in the case of the Middle and South regions). This assumption was also made in the population projection by the State Planning Commission. Note that currently the GDR population does not reach the replacement level, which is true for most of the developed countries.

On the other hand in some scenarios the death rates are expected to decrease to a level that leads to a life expectancy at birth of 75-77 years in 2030, a result of the improvement of health care and other living conditions which is a general aim of the socialist society. It was already mentioned that the GDR belongs to the group of countries having an extremely low infant mortality rate and small regional differences in death rates.

With regard to migration it is assumed that:

1. Berlin will be an important location for investment activities in the future, at least until 1990, which is also in accordance with the government program. This is connected with a further attraction of migrants from all regions and is expressed by its growing population in all scenarios.
2. The existing lack of labor force age groups, above all in the highly developed South region, requires measures for both an increase of the fertility rate, at least to the present national average (scenario 6), and a reorientation of the actual migration flows to the South region. The results of scenarios 5 and 6 show that the measures have to be much stronger than assumed here, to reach an essential change until the end of this century.
3. In accordance with recent migration patterns, in general a further decrease of migration flows can be expected between the large five regions. This results from a tendency to short-distance migration and also from the changing age structure of the population, which has a decreasing number of persons in the high mobility age groups.

5. Conclusions

In this paper the simulation package of multiregional population projections, available at IIASA, is applied to population projections of the five large regions of the GDR, which are the regions used for long-term territorial planning.

Information about future population development and regional distribution tendencies are essential for adequate planning.

In this sense multiregional population projections with different scenarios may contribute to the improvement of planning proposals. The possibility of changing demographic rates greatly improves the multiregional population projections that use only stable rates, which were the ones applied in all comparative studies of the NMOs. In the same way possible different territorial and economic strategies that influence regional population distributions, age structures, and growth can be studied.

This paper gives the results for a projection with stable rates as well as with changed rates. In nearly all scenarios the total population of the GDR is expected to decline. The main reason for this is that the country does not reach the replacement level, despite the high increase of the fertility rate in the second half of the 1970s. A further scenario could deal with a considerable increase of fertility.

It could be shown that the main contributor to the population loss of the country would be the densely populated South region with its continuous negative natural increase rate and its high migration loss. The problems of this region and possible changes are discussed in several scenarios.

In future work it will be necessary to study changing migration patterns within large regions, because two-thirds of all migrations occur within the districts. They have a great influence on population redistribution between different settlementsize groups. The main problem of this task is the availability of detailed statistical data (for instance, the differentiation by age groups) for small regional units.

The simulation model used in this paper is an important tool to study a multiregional population system. Few suggestions can be made in order to improve the model. The first one is that there should be an option to deal with both sexes simultaneously.

The second one is that the variable gross death rate should not be taken as a scenario variable. That is because the GDR is much more affected by death rates in older age groups than in younger ones. Therefore it would be better to use another scenario variable instead of growth death rates, such as, for example, life expectancy.

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Averaging Life Expectancy[1]

Evgenii Andreev, Wolfgang Lutz and Sergei Scherbov

1. When the Average is Lower Than Either Value

In a recent paper Scherbov and Lutz (1989) calculate scenarios on future mortality trends in the republics of the Soviet Union. The latest available information for 1986 indicates that female life expectancy was lowest in Turkmenistan with 67.8 years and highest in Lithuania with 75.9 years. The all-union average for female life expectancy lies at 73.8 years. One scenario assumed that mortality curves would be shifted up and down to con verge to the same level of life expectancy in all republics by 2020. The results for 2019 (see Table 1) show that the difference between the republics is already minimal[2] but most surprisingly showed that the average life expectancy for the Soviet Union was lower than the life expectancy in any of the 15 republics.

A first analysis of this phenomenon reveals the following: it is not a mistake in the calculations but a quite possible result of the fact that different shapes of the force of mortality function in the various republics are aggregated using different age structural weights. In the Central Asian Republics infant and child mortality is very high relative to mortality at older ages, whereas in most European republics old age mortality is higher; this differential in the age pattern of mortality together with the fact that the age structure in Asia is much younger than in Europe (see Table 1) results in an aggregate life expectancy

Table 1. Projected population distribution for the republics of the Soviet Union under the assumption of life expectancy converging by 2020; women, year: 2019.

Republic	Population (thousands)	% Total	Mean age	Life expectancy
RSFSR	83964.898	47.171	40.175	77.831
UkrSSR	29354.686	16.491	40.186	77.962
BelSSR	5796.118	3.256	39.261	77.980
UzbSSR	18526.979	10.408	28.699	77.750
KazSSR	11711.602	6.579	34.637	77.855
GrSSR	2818.267	1.583	39.631	77.933
AzSSR	4572.162	2.569	34.492	77.816
LitSSR	2143.815	1.204	39.698	77.976
MSSR	2820.524	1.585	35.628	77.781
LatSSR	1475.366	0.829	41.032	77.811
KirSSR	3431.611	1.928	30.183	77.713
TadSSR	4712.997	2.648	27.706	77.790
ArmSSR	2304.101	1.294	36.657	78.026
TurkmSSR	3435.693	1.930	28.017	77.730
ESSR	933.012	0.524	39.896	77.825
USSR	178001.812	100.000	37.559	77.632

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[2] Variations are partly due to the iteration procedure used.

Table 2. Example of a simple case where the harmonic mean of the aggregate lies outside the range of the two individual means.

	Group A			Group B			
	Size	Events	Rate	Size	Events	Rate	Harmonic Mean
Region 1	100	95	.95	300	30	.10	.181
Region 2	200	10	.05	400	80	.20	.080
Both Regions	300	105	.35	700	110	.16	.217

(calculated by adding up deaths and risk populations for each age group) that is lower than the life expectancy in the individual republics.

The above described case is certainly not the only empirical case in which the aggregate life expectancy lies outside the range of its constituents. It becomes intuitively clear that always when mortality curves cross and the age structure of the two populations is sufficiently different, the phenomenon may occur. The phenomenon is also not restricted to life expectancy but might occur with a large number of non-linear averaging functions. To illustrate this point, consider the harmonic mean as a simple example of non-linearity. Table 2 lists two regions, each of them consisting of two groups with different intensities of a given event. While the harmonic mean of the two groups in Region 1 is .181 and in Region 2 .080 and aggregation of the two regions yields a mean of .217 which is clearly greater than any of the two regional means.

Despite the possible generalization of the phenomenon to an infinite number of non-linear functions we will restrict the analysis in this research note to the concrete questions that arise when averaging life expectancy. We will ask for the conditions under which, generally, the average life expectancy calculated by aggregation of the age groups is different from the arithmetic mean of the individual life expectancies weighted by the proportions of births and, in particular, under which conditions the aggregate life expectancy lies outside the range of its components.

The question will be approached in several steps: first, a comparison between different stable populations is given; next, two theorems are proven for specific cases; to estimate the probability of the phenomenon for real populations the parameters of the Brass logit life table are modified step by step by simulation to cover all possible regional mortality patterns; finally, a stable multi-state case with migration is considered and conclusions are drawn.

2. Two Stable Populations

Illustrating the phenomenon in the case of two stable populations might make the underlying dynamics clearer than in the heuristic case of the Soviet republics described above. Assume a stable shrinking population with an intrinsic growth rate of -0.005 (population 1) and another with a growth rate of +0.010 (population 2). Population 1 which might stay for an aged European society has a relatively higher mortality above age 20 and lower under age 20 than population 2 which might resemble an Asian pattern. The mortality schedules plotted in Figure 1 result from the Brass logit life table with the following parameters: $\alpha = -1.100$ and $\beta = 1.162$ in the case of population 1 and $\alpha = -0.627$ and $\beta = 0.230$ in the case of population 2. Figure 2 gives the resulting stable age distributions.

In this example the life expectancy for population 1 is 71.14 years and that for population 2 is 73.08 years while the joint life expectancy of both populations lies with 69.26 years far

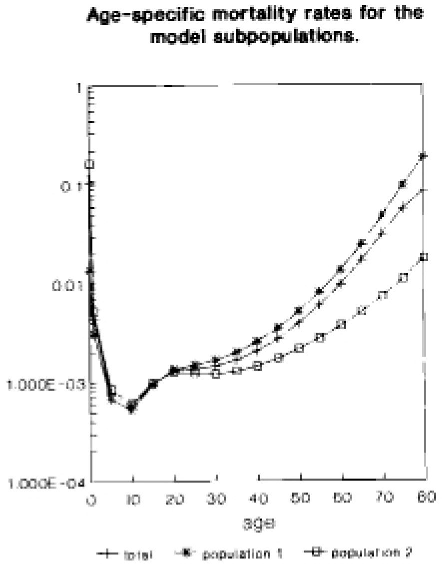


Figure 1. Two selected mortality schedules and their average.

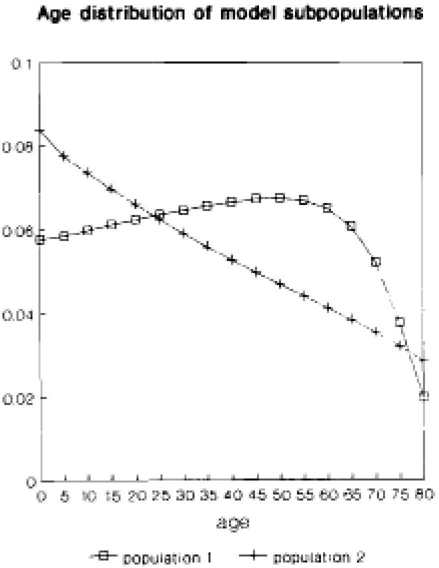


Figure 2. Stable age distributions for the two populations.

below the expectancies of both individual populations. Loosely spoken, we may say that the combined population suffers from bad features of both sub-populations: below age 20 the joint force of mortality function is closer to the high child mortality in population 2 and above age 20 it is closer to the higher adult mortality of population 1. This follows directly from the age-distributional weights plotted in Figure 2 which are greater for population 2 at the young age and for population 1 at ages 25 to 75.

3. Two Certain Statements

Suppose that a population is a sum of two sub-populations with different mortality curves that are crossing. We assume that the size of the combined population in each age group is greater than zero. Let y_a denote the proportion of the first sub-population of the total population of age a. We shall consider the discrete mortality model with $a = 0,1,\dots,w$; where w is the highest age of survivors. Suppose that y_a is a random variable with linear distribution function $0 \le y_a \le 1, and\, Y = (y_0,\dots,y_{10})$ is a random vector, whose coordinates are independent.

In the following theorem we shall show that in the case that expectations of life at birth are equal at some time interval, the probability that the aggregate life expectancy has the same value is zero.

A: Let $m_a^{(i)}$ denote the age-specific mortality rate in the whole population, first and second sub-population correspondingly where $a = 0,1,\dots,w$ and $i = 0,1,2$. Then

$$m_a^{(0)} = m_a^{(1)} \cdot y_a + m_a^{(2)}(1 - y_a) \tag{1}$$

and there exists an age $\tilde{a}$, where

$$\frac{dm_{\tilde{a}}^{(0)}}{dy_{\tilde{a}}} = m_{\tilde{a}}^{(1)} - m_{\tilde{a}}^{(2)} \neq 0 \tag{2}$$

because mortality curves are different.

The life expectancy is a function of age-specific death rates. We can assume that this function has continuous negative first partial derivatives. These assumptions follow from well-known life expectations calculation procedure and mathematical demography formulas (reference). So we can write for the aggregate population

$$e_0^{(0)} = f(m_0^{(0)},\dots,m_w^{(0)}) \tag{3}$$

and

$$\frac{\partial f(m_0^{(0)} \cdots m_w^{(0)})}{\partial m_a^{(0)}} < 0 \tag{4}$$

for each value a and $m_a^{(0)}$.

Substituting (1) to (3) and (2) in (3) to (4) we obtain that

$$e_0^{(0)} = f(Y) \quad \text{and} \quad \frac{\partial e_0^{(0)}}{\partial y_{\tilde{a}}} \neq 0$$

when $0 \le y_{\tilde{a}} \le 1$. Consequently, the set $\{Y, f(Y) = const\}$ is a surface, whose dimension is less than w. This means that the probability of life expectancies being equal is zero.

B: Now, suppose that expectations of life of sub-populations correspondingly are $e_0^{(1)}$ and $e_0^{(2)}$, $e_0^{(1)} < e_0^{(2)}$, but mortality curves are crossing. Then a set of ages exist, where $m_a^{(1)} < m_a^{(2)}$. We shall show that the probability of $e_0^{(1)} < e_0^{(0)} < e_0^{(2)}$ is less than 1.

Let $\tilde{y}_a = 1$ if $m_0^{(1)} < m_0^{(2)}$ and $\tilde{y}_a = 0$, if $m_0^{(2)} \le m_0^{(1)}$, then $\tilde{m}_a^{(0)} \le m_0^{(2)}$ for each a, and such an age $\tilde{a}$ exists that $\tilde{m}_{\tilde{a}}^{(0)} < m_{\tilde{a}}^{(2)}$. Using (4) we obtain

$$\tilde{e}_0^{(0)} = f(\tilde{Y}) > e_0^{(2)}.$$

Since $,f(Y)$ is a continuous function there exists a $e > 0$, that $f(Y) > e_0^{(2)}$ if $|y_a - \tilde{y}_a| < e$. This means that the probability of $e_0^{(1)} < e_0^{(0)} < e_0^{(2)}$ is not greater than $1 - e^{10}$.

The analytical approach does not allow to estimate this probability more precisely and we do not know conditions under which $e_0^{(2)} < e_0^{(0)}$ $(or\ e_0^{(0)} < e_0^{(1)}$ and the variable Y takes a more realistic value than "O" or "1". Such an estimate, however, might be found by simulation.

4. Estimating the Proportion of Cases Where the Aggregate Life Expectancy Lies Outside the Range by Simulation

The above approach could prove two important theorems but did not yield a realistic estimate of Y other than the fact that it must be smaller than 1. Another approach is through simulation. For this purpose we first have to define the possible range of mortality patterns to be considered. We chose to do this by using the Brass logit life table approach and expressing the complete range of regional model life tables at different mortality levels in terms of the two parameters α and β in the Brass model (Brass et al. 1968).

Figure 3 graphically presents the space defined by the four regional types of model life tables defined by Coale-Demeny (Coale & Demeny 1966) and the five regional tables defined by the UN (United Nations 1982) with life expectancy levels ranging from 60 to 80 in steps of 2.5 years. All together this results in 81 data points that spread over a range from (3-values .85 to 1.4 and a-values between -1.5 to -0.5, with a concentration of points in the lower left corner.

Based on these 81 possible mortality patterns, couples of non-identical mortality schedules were randomly chosen and if the difference in life expectancy did not exceed 3.0 years they were combined with a set of two intrinsic growth rates randomly chosen from within the range -0.005 to 0.02. The three-year limit and the range of intrinsic growth rate were chosen in order to avoid cases unlikely to occur in reality. 100,000 such pairs of populations were randomly generated. Their distribution with respect to the relative position of the aggregate life expectancy is plotted in Figure 4. The x-axis gives the difference between the aggregate life expectancy e_{tot} and the lower life expectancy of the two given population (e_{min}) divided by the difference between the two $(e_{max} - e_{min})$ (this indicator is denoted in the figure as e). On the y-axis the distribution of the 100,000 pairs is given on a logarithmic scale. The distribution is heavily concentrated around the arithmetic mean of the two life expectancies. In other words, in the majority of likely empirical cases the aggregate life expectancy lies close to the center of the distance between the two life expectancies. In 80.5% of all simulated cases the aggregate mean lies within the range given by the two life expectancies. But in almost one fifth of all cases it lies outside the range.

This numerical estimate only gives a very rough indication of the empirical likelihood of the phenomenon that the aggregate life expectancy may lie outside the range of the life expectancies in the populations that constitute the total. It is subject to the above stated model assumptions and limitations. But the simulations show that the phenomenon initially described for the Soviet Union is not a marginal event that might be neglected empirically.

A further point of interest is the question to what extent the difference between life expectancies within a given couple of populations determines the likelihood of the mean to lie outside the range. For this purpose a different set of simulations was carried out that reveals a very smooth and monotonically declining association between the differences in life expectancies and the frequency of the mean lying outside the range (see Figure 5).

In the case of equal life expectancies (difference zero) theorem A above showed that the aggregate expectancy must be different (with probability one) if the force of mortality functions are not identical. For a difference of half a year between the two life expectancies in about half of the 10,000 simulated cases the aggregate life expectancy lies outside the range of that in the two sub-populations. For a difference of two years this happens only in 20% of the cases. For greater differences this frequency seems to converge to a level of around 5% (for 10 years 0.0535). In Figure 5 each data point is based on a simulation of 10,000 cases.

From the above described simulations we may conclude that the probability for the aggregate life expectancy to lie outside the range of its components is clearly a function of the difference in life expectancies. Of the empirically plausible cases with a difference of three or less years the frequency of lying outside the range is about 20%.

5. Sensitivity to the Growth Rate of the Stable Population

In the cases described above the central point of interest was in the difference between underlying mortality schedules. Assumptions on the intrinsic growth rates of the stable populations considered had to be made but were not studied systematically. In this section we want to study the sensitivity of the phenomenon with respect to changes in the intrinsic growth rates.

Figures 6a and 6b give shaded contour maps on the dependence of the aggregate life expectancy on the intrinsic growth rates r_1 and r_2 of stable sub-populations with randomly chosen mortality schedules (stated in the legend of Figures 6a and 6b). The intrinsic rates

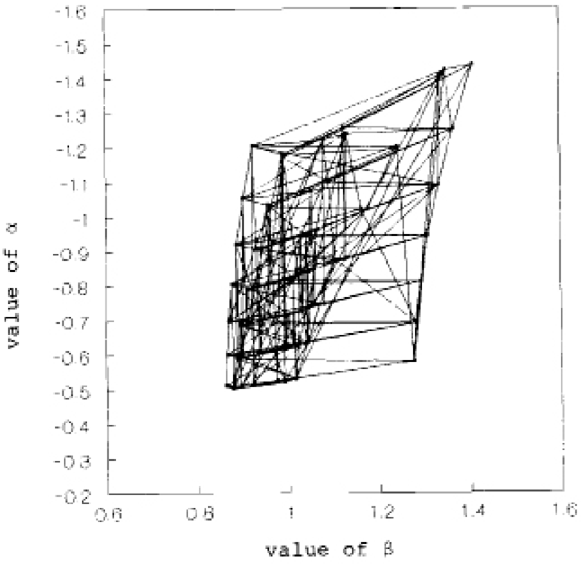


Figure 3. Space defined by the four Coale-Demeny and five UN regional life tables with life expectancy ranging from 60 to 80 in steps of 2.5 years and expressed in terms of the parameters α and β from the Brass logit life table.

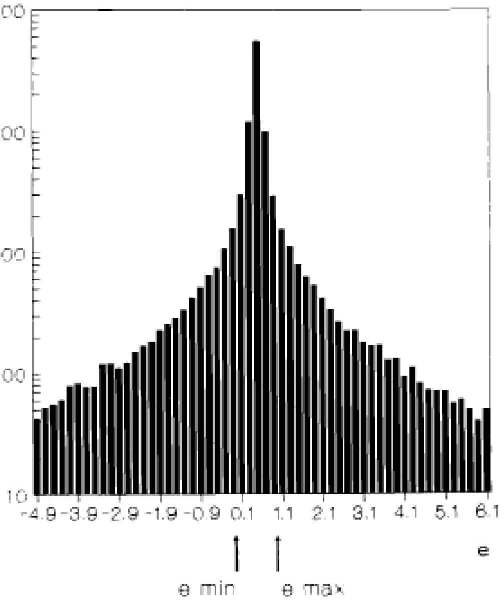


Figure 4. Distribution of the mean life expectancy of 100,000 randomly chosen pairs based on the 81 points shown in Figure 3 with a maximum difference in e_0 of 3 years.

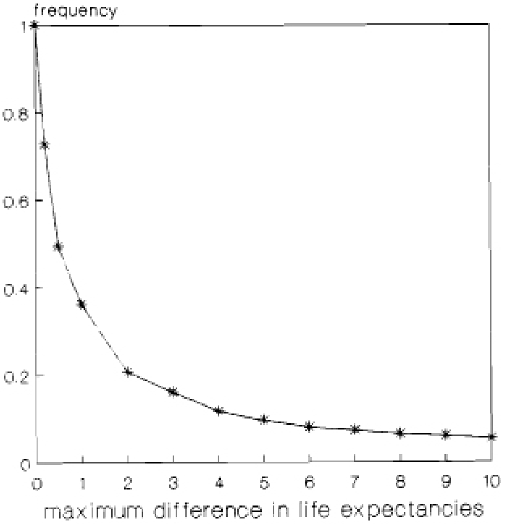


Figure 5. Dependence of the frequency of the mean lying outside the range on the difference between the two life expectancies considered (each point based on 10,000 simulated cases).

considered range from -.005 to +.020. The graph clearly indicates that only in the cases when the growth rates are similar to each other the aggregate life expectancy lies within the range of the expectancies of the two sub-populations (indicated in the graph by the flat area). In all other cases the aggregate expectancy lies outside the range.

Since it has been indicated in the previous section that the probability of the mean to lie outside the range depends on the difference between the life expectancies considered the pictures are given for differences of one year (Figure 6a) and three years (Figure 6b). Naturally the proportion of means lying outside the range is greater in the first case.

6. Two Regions with Migration

Are such cases where mortality schedules and stable age distributions cross likely to occur in neighbouring or otherwise related populations that are natural candidates for aggregation or is the described phenomenon without practical consequences? In the case of migration between two related regions the above described conditions may easily become true. Think of two provinces of a country or even urban and rural areas within the same province where it might well be the case that in one area child mortality is higher whereas in the other adult mortality is greater. And due to an unbalanced migration pattern on top of fertility differentials the population age structures are different. What will the averaging be like in this case?

Consider population 1 (urban) with a life expectancy of 70.69 and population 2 (rural) with 70.06. Fertility is somewhat higher in population 2 and there is a stream of migrants from 2 to 1 with an age profile that peaks at ages 20-25. The resulting population age structures are plotted in Figure 8. This might be typical for the situation of any town that draws from the surrounding rural areas.

Table 3 presents the life expectancies for periods and cohorts resulting from different ways of averaging. Aggregating the deaths and the risk populations from both sub-populations and calculating life expectancy based on the resulting age-specific death rates

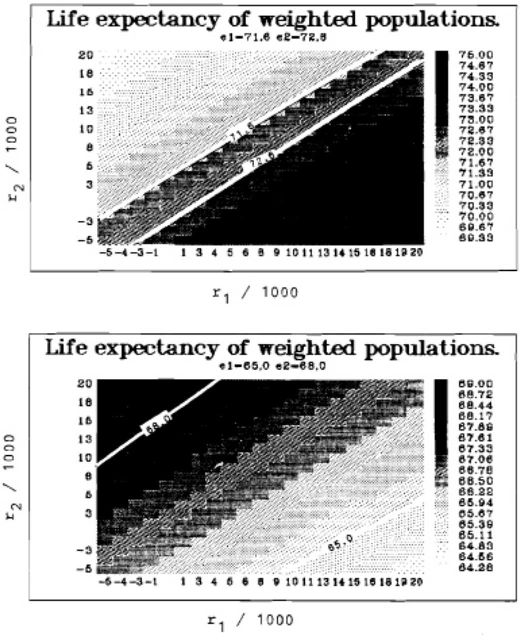
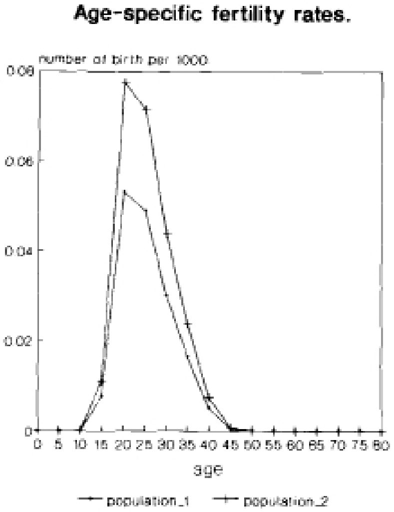


Figure 6. Shaded contour maps of average life expectancies in dependence on the growth rates of the stable populations considered for two selected pairs of life expectancy.



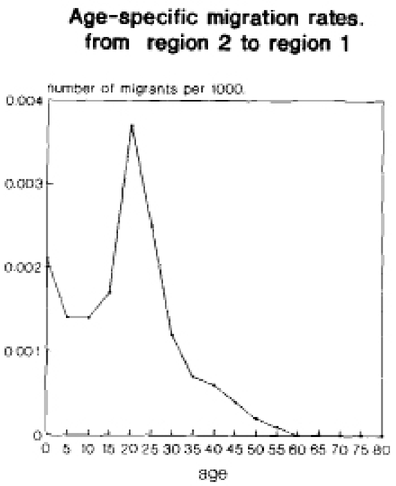


Figure 7a. Age-specific fertility rates in example considered.

Figure 7b. Age-specific migration rates from region 2 to region 1 in example considered.

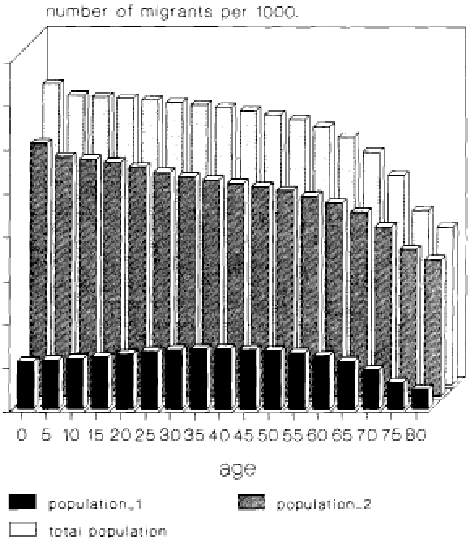


Figure 8. Population age structure m example considered (total population makes 1000).

yields a joint life expectancy of 69.92 that is smaller than the expectancy in any of the two populations. An alternative and widely-used method is to average the life expectancies for the two populations by weighting them with the proportions of newborn. In this case the life expectancy must clearly lie within the range and comes to 70.15 in our case.

Which of these two approaches that both seem to be straightforward and plausible is the “right one”? One criterion to find a decision is the question: which one resembles better the experience of a real cohort? A multi-state model for real cohorts results in a life

Table 3. Simulation of survivorship in a two-region population system.

Life expectancy	Total population	Population 1	Population 2
based on age-specific death rates	69.92	70.69	70.06
based on regional proportion of newborns	70.15	70.69	70.06
for real cohorts:			
total	69.92	70.69	69.79
in region 1	13.67	70.69	3.67
in region 2	56.25	0.00	66.13

expectancy for the joint population that is equal to that resulting from the first approach based on summing up age-group wise. However, for a cohort the aggregate life expectancy clearly must lie between the two cohort life expectancies for populations 1 and 2 because there may be no influence of the age structure. Indeed, Table 3 shows that this is the case. The difference to the period pattern described in the upper half of the table is that for population 2 the cohort life expectancy at birth is lower than the period life expectancy. This is a result of the migration from 2 to 1. Part of the population born in region 2 will not die in region 2 but in region 1. But since old age mortality is higher in region 1 than in region 2 the migrants will live shorter in region 2 than they would have in region 1. (This of course assumes that each person is exposed to the mortality risk of the region in which he lives.) On the average people born in region 2 live 66.13 years in that region and 3.67 years in region 1. Together this makes only 69.79 years. For region 1 there is no difference between cohort and period life expectancy because all people born in region 1 stay there until they die.

7. Alternative Approaches to Life Expectancy

Some authors consider the calendar year life expectancy as a cumulative indicator of the mortality level; other authors see the period life expectancy as analogous to the cohort and consequently calculate the total life expectancy as a weighted mean of the sub-population's life expectancies weighted by the proportions of birth.

In the case of a stable system of closed sub-populations and stable mortality curves such period life expectancy really is equal to the life expectancy of the cohort. This is not true, however, in the case of migration between sub-populations. In a stable system of sub-populations with migration the cohort life expectancy is equal to the period aggregate life expectancy calculated by adding up deaths and risk populations for each age group in the way we did it in this paper. And in this case it may occur that the cohort life expectancy (being identical to the above described average period life expectancy) lies outside the range of the period life expectancies of the stable sub-populations such as in the example given in Table 3. This is in contradiction with the attempt to interpret period life expectancy in terms of real cohorts. Hence, weighting two period life expectancies in a cohort-like manner with proportions at birth is not correct in the case of migration.

For averaging life expectancies of closed populations (such as averaging male and female life expectancy) the situation is less clear. Whether to aggregate the populations age group wise or weight the expectancies by proportions at birth remains a more philosophical question depending on whether period life expectancy is just viewed as a summary indicator of mortality or as an analogon to real cohort life expectancy.

A possible next step of analysis is to apply the results of this paper also to models of cause-specific mortality analysis. In the cases of cause-deleted mortality tables, cause-specific death probabilities and mean ages at death from a certain cause, similar averaging problems appear.

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Significance of Life Table Estimates for Small Populations: Simulation-Based Study of Standard Errors[1]

Sergei Scherbov and Dalkhat Ediev

1. Introduction: Data and methods

Life expectancy is a key characteristic of human longevity and development, and policies worldwide aim to increase it. While effective policies can be based on informative monitoring systems, estimating life expectancy for small populations may run into difficulties because of the small number of events and insufficient exposures, which lead to uncertainty in estimating death rates. This makes the development of methodology for estimating and comparing life expectancy for small populations a high priority.

Using the Monte Carlo simulation approach, Silcocks, Jenner, and Reza (2001), Toson, Baker, and the Office of National Statistics (2003), Eayres and Williams (2004), as well as Williams et al. (2005) evaluated methodologies for the estimation of small-area life expectancy in the United Kingdom (UK) context. They showed that life expectancy at birth is distributed normally and estimates of its standard error are distributed with a significant skew for the small population size. They also demonstrated that traditional life table methodology without special corrections for age bands with zero deaths in a small population performs quite well, and that the choice of the minimum age of the open age interval and modeling the mortality in that interval are important for estimating life expectancy and its standard error. Based on the simulated dependency of standard errors on population size, a minimum population years-at-risk size of 5,000 for estimating life expectancy at birth was recommended in the UK context. However, the age composition of a small population in all the tests was fixed and was only scaled up and down depending on the simulated population size. Apart from that, the effects of life expectancy level on estimation accuracy were not explored. In this paper we extend previous research by including the effects of population age composition and life expectancy level.

Our work extends the previous research in several directions. First we confirm some of the findings in the literature in a wider context of mortality schedules and population structures. We conduct simulations based on all available male and female life tables for Austria, Italy, Japan, Spain, Sweden, and the UK, which were chosen as being representative of the variety of mortality situations in currently low-mortality countries. We use data from the *Human Mortality Database* (University of California, Berkeley & Max Planck Institute for Demographic Research 2010). For each life table scrutinized, we consider five stable population age compositions corresponding to -2%, -1%, 0%, 1%, and 2% annual population growth rates. Based on those mortality and population schedules, we consider eight population sizes of 1,000, 5,000, 10,000, 25,000, 50,000, 100,000, 250,000 and 1 million people (in total, 43,680 populations).

Second we present the empirical relations between the standard error of life expectancy indicators and the corresponding life table and population characteristics (life expectancy, and population growth rate). Third we evaluate standard errors for both the life expectancy at birth and the life expectancy at age 60—two measurements that are essential in the context of policies oriented toward population aging and pension systems. Fourth we

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provide a more in-depth analysis of the normality of life expectancy estimates for small populations, and illustrate that age composition can crucially affect the normality of estimates (which is important for establishing confidence limits and the significance of the variation observed in terms of life expectancy).

In contrast to previous work, we consider indicators of unabridged life tables. We also study the estimates for abridged life table calculations based on the age groups 0, 1, 5, 10, ..., 85+ years. However both the previous work and our own study (not reported here) indicate that using abridged as opposed to unabridged life tables has only a small effect on estimation accuracy compared with the procedure chosen for the open age interval. At the same time, we find that estimates for abridged life tables tend to be systematically biased when the age composition deviates from that of the stationary population, irrespective of the population size. (These distortions are caused by a deviation from the stationary age composition within individual age intervals.) Therefore avoiding the use of abridged life tables is recommended unless the age composition of the population is fairly close to stationary.

In the three works cited above, the open age interval was chosen to start at 85, 90, or 95 years; if no deaths occurred in the open age interval, the corresponding mortality rate was taken from a known life table and not from the simulated population. We use a different approach, adjusting the open age interval in such a way that there is at least one death in it; hence, we do not use (unavailable in practice) rates from a theoretical life table in order to infer a life table for the simulated population.

In this paper we present auxiliary formal relations and describe how the simulations are designed; we then continue with a discussion of life table calculations, followed by the presentation of results. We conclude by presenting illustrative case studies and general recommendations. The paper is supplemented by an Appendix with tabular material.

2. Preliminary formal considerations and simulations design

Our study is based on simulations, as analytical approximations of standard errors of life expectancy estimates (Chiang 1984) are biased for small population (Eayres & Williams 2004). However formal considerations are still useful for understanding the mechanism behind the standard errors and biases of life expectancy estimates. Those considerations are in this section.

The model

Individuals in a population of size N_x at exact age *x* all have a probability of dying q_x during one year. There is no migration. The number of deaths is binomially distributed.

A maximum likelihood estimator of q_x is $\hat{q}_x = \frac{D_x}{N_x}$ where D_x is the observed number of deaths (Chiang 1984, eqs. (5.1) and (5.12)). The variance of $\hat{q}_x$ equals $\frac{q_x(1-q_x)}{N_x}$, which can be estimated as $\frac{\hat{q}_x(1-\hat{q}_x)}{N_x} = \frac{\hat{q}_x^2(1-\hat{q}_x)}{D_x}$ (Chiang 1984, eqs. (3.7) and (3.8)).

Assuming a constant force of mortality m_x, the death probability q_x equals $1-\exp(-m_x)$.

The occurrence-exposure rate $\hat{m}_x = \frac{D_x}{P_x}$ (P_x stands for the population person-years exposed at age *x* to *x*+1, which may be approximated by the mid-year population for all age groups except the youngest and oldest ones) is a maximum likelihood estimator of D_x. It is unbiased, consistent, and asymptotically normal when the number of deaths (D_x) is large (Rao 1973; Chiang 1984). The asymptotic variance of $\hat{m}_x$ equals $\frac{m_x(1-q_x)}{P_x}$ (Chiang 1984, eq. (3.5)). Using the constant force of mortality assumption and the invariance properties of maximum likelihood, one finds that $\hat{q}_x = 1-\exp(-\hat{m}_x)$.

The model described above is applied to each of a number of age intervals (*x*, *x*+1), with age *x* running from 0 to 109, while *x*=110+ represents the open interval for the highest ages. Independence across ages is assumed.

Why a bias in life expectancy estimates?

We begin by illustrating why and how life expectancies can be biased when they are estimated from small population data.

In his classic monograph, Chiang (1984, p.161) shows that sample life expectancy is "an unbiased estimate of the corresponding unknown true expectation of life." This conclusion was based on the assumption that "the observed expectation of life [life expectancy calculated from observed death rates—Scherbov and Ediev] at a given age is the sample mean lifetime of individuals living beyond this age." Yet, such an assumption can only be asserted for cohort life tables obtained from observations over individual lifetimes. In our study we focus on estimates of period life expectancies; therefore, Chiang's proposition about non-bias in the life expectancy may be violated (and, indeed, is, as follows from our and others' simulations and the following formal relations).

Consider first the estimate of probability of surviving to a given age, which is a function of accumulated mortality rates $\hat{m}_x$ (these represent the mortality rates and not the individual lifetimes upon which the period life table calculations are based):

$$\hat{l}_x \approx e^{-\sum_{y=0}^{x-1}\hat{m}_y} \tag{1}$$

Mortality rates are unbiased estimates of the underlying theoretical rates: $E(\hat{m}_x) = m_x$ (Chiang 1984). Separating the expected values in (1) and expanding by Taylor's theorem, yields:

$$\hat{l}_x \approx e^{-\sum_{y=0}^{x-1} m_y} e^{-\sum_{y=0}^{x-1}(\hat{m}_y - m_y)} = l_x e^{-\sum_{y=0}^{x-1}(\hat{m}_y - m_y)} \approx l_x\left(1-\sum_{y=0}^{x-1}(\hat{m}_y - m_y)+\frac{1}{2}\left[\sum_{y=0}^{x-1}(\hat{m}_y - m_y)\right]^2\right). \tag{2}$$

Hence, assuming independence and non-bias in individual mortality rates, the estimated survival probability is biased upwards:

$$\begin{aligned} E(\hat{l}_x) &\approx l_x - l_x\sum_{y=0}^{x-1}E(\hat{m}_y - m_y)+\frac{1}{2}l_x E\left(\left[\sum_{y=0}^{x-1}(\hat{m}_y - m_y)\right]^2\right) = \\ &= l_x + \frac{1}{2}l_x E\left[\sum_{y=0}^{x-1}(\hat{m}_y - m_y)^2\right] = l_x + l_x\frac{1}{2}\sum_{y=0}^{x-1}\sigma^2(\hat{m}_y) \end{aligned} \tag{3}$$

Similar relations apply to the probabilities of surviving from a given age *x* to another given age *a*. The life expectancy is the sum of such survival probabilities, which explains why it must be biased upwards. The results of adding more terms into the Taylor series expression in (3) cannot be exactly calculated analytically. However, at small population sizes the third central moment of binomial distribution is negative (at typically low mortality levels, the occurrence-exposure rate $\hat{m}_x = \frac{D_x}{P_x}$ is approximately proportional to the binomially distributed enumerator). Therefore, both third- and fourth-degree terms in the Taylor expansion yield additional upward bias.

How are biases related to population size?

As noted above, variance of the occurrence-exposure mortality rate is inversely proportional to the population exposed P_x in the respective age group; asymptotically (Chiang 1984),

$$\sigma^2(\hat{m}_x) = \frac{m_x(1-q_x)}{P}. \tag{4}$$

Hence, bias in (3) and in life expectancies must increase as population size decreases. eq. (4) also suggests that as population size increases, standard errors of estimates of life expectancy decrease (asymptotically) as an inverse square root of population size.

How are standard errors related to population size?

To roughly estimate variance of the survival probability, we drop the quadratic term in (2):

$$\sigma^2(\hat{l}_x) \approx \sigma^2\left[l_x\left(1-\sum_{y=0}^{x-1}(\hat{m}_y - m_y)\right)\right] = l_x^2 \sum_{y=0}^{x-1}\sigma^2(\hat{m}_y), \tag{5}$$

which, given eq. (4), implies that the standard errors of survival probabilities are asymptotically inversely proportional to the square root of the population size. The same applies to the probabilities of surviving from one given age to another and to life expectancy. At small population sizes when the contribution of the third and fourth moments in the Taylor series become considerable, there is an additional increase in standard errors. This effect is also visible in simulations. In our study the inverse proportionality between the standard errors and the population size may be used for populations of at least 5,000 people.

How skewed are the distributions of the estimates?

The relation of survival probability to mortality rates is also indicative of how skewed its distribution might be. At typically low mortality levels, the occurrence-exposure rate $\hat{m}_x = \frac{D_x}{P_x}$ is approximately proportional to the binomially distributed and not skewed enumerator. A full Taylor's expansion in (2) would combine non-skewed distributions generated by odd-powered summands and positively skewed distributions generated by even-powered summands. Hence, survival probabilities (and thus life expectancies) must be positively skewed. This means, in particular, that at sufficiently small population numbers, the distribution of life expectancies will deviate from normal.

On Chiang's approximation

Chiang (1984, pp.161–165) proposed a useful method for approximating standard errors of life table estimates for small areas. His recurrent method was based on first-order approximation to Taylor's series of life expectancy as a function of survival probabilities. Earlier studies (Toson et al. 2003; Eayres & Williams 2004) suggested, in the UK context, the effectiveness of Chiang's approximate method. Eayres and Williams report a good fit of the method for the standard error of life expectancy at birth at large population sizes; yet, at population size 5,000 the reported bias of the method already amounts to a decimal digit. We also studied the method using Japanese female life tables in 1947, 1977, and 2007 and came to results similar to those reported earlier. We found that the method yields strong biases at small population size (in our simulations, the method underestimates, on average, the standard error of life expectancy at birth by up to 0.3 years at population size 5,000 and by up to 0.8 years at population size 1,000; those biases are up to 0.4 and 6 years, respectively, for the life expectancy at age 60). At large population size, its bias, being small in absolute value, amounts to 5% of the true standard error (results are similar for life expectancy both at birth and at age 60). A drawback, in the context of our study, of Chiang's method for the standard errors is its inability to provide sample distributions of the estimated life expectancies and their standard errors. Therefore, our prime method of studying the standard errors in the work was based on simulations, and not on Chiang's approximation. Although Chiang's method may be used without significant problems starting from a population size of about 10,000, we also provide ready-to-use tables, which might be more convenient in practice at any population size.

Simulation design

Each life table defines a stationary population (e.g., Keyfitz 1977). For one particular life table, we selected a certain population size N, and simulated populations with sizes N equal to 1,000, 5,000, 10,000, 25,000, 50,000, 100,000, 250,000 and 1 million people. The life table defines a probability of dying qx at each age interval. Given N, we also know the number of people Nx at each age x. The number of deaths in each age interval was drawn from a binomial distribution with probability qx and size Nx. One simulation run resulted in one specific value for the number of deaths in each age interval. This resulted in one life table and one set of values for the life expectancies at various ages. Repeated simulation gave us many sets of such life expectancies, and we report below the average values and standard errors of e_0 and e_{60} across all simulations.

In addition to the case of a stationary population, we also simulated life tables based on stable populations with growth rates *r* equal to -2%, -1%, +1%, and +2%. For a given life table and a given growth rate *r*, the age structure of the corresponding stable population can be constructed (e.g., Keyfitz 1977). Given the size *N* of each stable population, we computed N_x, the number of people at each age *x*, and simulated life tables and life expectancy values as described above for the case of a stationary population.

How many simulations per sample?

The number of simulations used in our study (25,000) is considerably higher than that used in the previous literature (2,000 by Silcocks et al. 2001; as well as Toson et al. 2003; 10,000 by Eayres & Williams 2004). Such a high number was chosen so as to reduce statistical errors of the outcome of the simulations to an acceptable minimum, as described next. The standard error of normal sample standard error S is given as $\sigma_S \approx \sigma \frac{1}{\sqrt{2(n-1)}}$, where σ is an unknown standard deviation estimated by n, and n is the sample size (Ahn & Fessler 2003). At $s_0 = SD_0\sqrt{N/1000}$, the standard error amounts to about 1.6% of the standard deviation, which, being relatively small, may nonetheless considerably affect the outcome of the estimates (especially given the need to study the normality of the estimates and their confidence limits). We increased the number of simulations to 25,000 so that the relative standard error of the standard error falls below 0.5%.

3. Life table procedures. Imputations for the open age interval

Small population size creates specific problems when a life table is being constructed in the usual way (see details in Eayres & Williams 2004). In particular, the absence of deaths at the open age interval implies immortality. Toson, Baker, and the Office of National Statistics (2003) as well as Eayres and Williams (2004) showed that life tables with zero death rates at age groups other than the open age group perform better than those with artificially imputed low death rates (we also came to a similar conclusion based on simulations of the Russian case, not presented here).

For the open age interval, Toson Baker, and the Office of National Statistics (2003) and Eayres and Williams (2004) proposed to impute an externally determined mortality (e.g., from the national life table) for the open age interval with no deaths observed. We have examined this method and, indeed, extra knowledge about mortality at open age intervals improves the life expectancy estimates considerably. However in many practical cases there is no basis for assuming that old-age mortality in a certain small population will be exactly the same as that observed elsewhere or on a nationwide basis. Often the very purpose of estimating life expectancy for small areas is to reveal the differences; for this purpose imputing standard mortality at open age intervals may not be sufficient.

We therefore present here an alternative approach, where the boundary of the open age interval is lowered to such a level (from the original level of 110 years) that it comprises at least one observation of death. As rough as it may be, this method performed better in our simulations than alternatives with a minimum of 2, 3, …, 7 death observations in the open age interval (we do not present the results for those alternatives here). Except for very small and growing populations, standard errors of life expectancy estimates produced by this method were comparable to standard errors of estimates produced by imputing the theoretical mortality from the original life table for the open age interval. For a stationary population of 1,000 people, the former standard error is about 20% higher than the latter; for 2,000 people it is 5% higher; for 5,000 people, 2% higher; and for a stationary population of 25,000 people, 1% higher.

4. Results

4.1 General overview

In this section we outline the general variation of estimation biases and standard errors according to population size, stable growth rates, and mortality levels. A more detailed analysis of the factors of standard errors follows in the sections below.

Although there are distinguishable differences in the results for males and females, the differences are far smaller than the standard errors themselves. We therefore pool all the results together, irrespective of the gender of the population.

Mortality level and population age structure, on the other hand, have strong effects on the outcomes. Standard errors for estimates of life expectancy at birth tend to peak at life expectancy at birth of around 50 years, while standard errors of life expectancy at age 60 increase monotonically as life expectancy at birth increases. Population growth increases standard errors for life expectancy at age 60, while its effect on standard errors for life expectancy at birth interacts with the level of the life expectancy.

The effect of the population size, the most important driver of standard errors, may be modeled as a square-root function, as suggested by the theoretical considerations above. Starting from population size 5,000, the standard errors rescaled to populations of 1,000 people—

$$s_0 = SD_0\sqrt{N/1000}\ , \tag{6}$$

$$s_{60} = SD_{60}\sqrt{N_{60+}/1000}\ , \tag{7}$$

$$s_{60} = SD_{60}\sqrt{N_{60+}/1000}\ , \tag{8}$$

—are already fairly constant, where SD_{60} and SD_{60} are the standard errors for life expectancy at birth and at age 60, respectively; *N* and N_{60+} are the total population size and population at age 60 and above. However with extremely small population sizes, the rescaled standard errors shift upwards. This problem is particularly strong for growing populations. We therefore present results separately for populations of 1,000 and 5,000 or more people.

4.2 Standard errors of life expectancy estimates

Simulated standard errors for life expectancy estimates at different levels of life expectancy at birth, population size, and growth rate are presented in Appendix, Table A1. In the table we present rescaled errors (6)–(8) obtained from simulations for populations of 5,000 and over. Results for the smallest population size (1,000) are singled out because, as noted above, the square-root approximation underestimates the standard errors for populations of this size.

There is a curvilinear association between the rescaled standard errors s_0 and the underlying true life expectancy at birth (see e.g., Figure 1 for stationary populations). This kind of association can be explained by a combination of processes with opposite effects in period mortality:

i. Decrease in infant and child mortality increases the role of adult mortality; this pushes up the standard errors of estimates of the life expectancy at birth. To see that, a stylized model with a known infant mortality may be considered, where $\hat{e}_0 \approx (1-q_0)\hat{e}_1$ and the variance $\sigma^2(\hat{e}_0) \approx (1-q_0)^2\sigma^2(\hat{e}_1)$ goes up when infant mortality declines. With declining infant mortality, the effect eventually levels off.

ii. An opposite effect is due to mortality compression (e.g., Fries 1980). As adult mortality decreases, the distribution of period life table deaths becomes more concentrated around the mean age at death. This also suppresses the standard error of the life expectancy estimate (our simulations suggest a tight positive association between the standard error of the life expectancy estimate and the standard deviation of life table age at death).

Despite the evident overall association between the life expectancy at birth and its standard error, the particularities of mortality age patterns may strongly affect the standard errors (note the case of Russian males also presented in the figure for illustrative purposes).

Therefore, the results of our study could be used in the context of mortality estimates (both contemporary and historical) in populations with mortality resembling that observed in modern developed countries. Situations with expected deviant age patterns of mortality must be addressed separately (e.g., by conducting additional simulations).

Standard errors of estimates of life expectancy at 60, not affected by the specific influence of infant mortality, follow a more consistent association with life expectancy at 60, irrespective of the population growth rate (see Figure 2 for standard errors averaged over all five population growth rates analyzed). The wide variety of simulated cases may be described by the following regression:

$$s_{60} = 0.082 \cdot e_{60} - 0.0010 \cdot e_{60}{}^{2} + err\,, \tag{9}$$

with a standard error of 0.04 years. Note that the relation applies at any population growth rate; the effects of population growth rate on age structure are well captured in rescaling (8) to a population of 1,000 persons at age 60+. Also note that eq. (9) yields, naturally, more accurate estimates than those presented in Appendix Table A1, where it is the life expectancy at birth that is used as the input variable instead of the life expectancy at age 60.

Table A1 demonstrates the importance of population age composition for accurate estimation of life expectancy in small populations. This suggests additional simulations may be required for populations whose age composition strongly differs from that of stable populations.

4.3 Biases

As suggested by the introductory theoretical considerations, there are upward biases in life expectancy estimates. The biases are notable for all population sizes up to 10,000 people.

For stationary and shrinking populations, the biases (for both life expectancy at birth and at age 60) amounted to about one year for populations as small as 1,000 people, and 0.2 years for populations of 5,000 people. For growing populations, these estimates must be doubled. However, the biases were significantly smaller than the standard errors of the life expectancy estimates. According to our simulations, estimation biases may be neglected for population sizes exceeding 10,000.

Given the strong dependency of the bias on age structure, we recommend that individual corrections in each specific case should be considered depending on the actual age composition of the population at a population size of under 5,000.

Simulations indicate that there is a significant association between estimation biases and standard errors. For the sample set of stable populations examined, we found the following regression relation which may be used to roughly assess the estimation bias for life expectancy at birth:

$$Bias_0 = 0.10 \cdot SD_0 + 0.015 \cdot SD_0{}^{2} + 0.050 \cdot SD_0 \cdot r + err \tag{10}$$

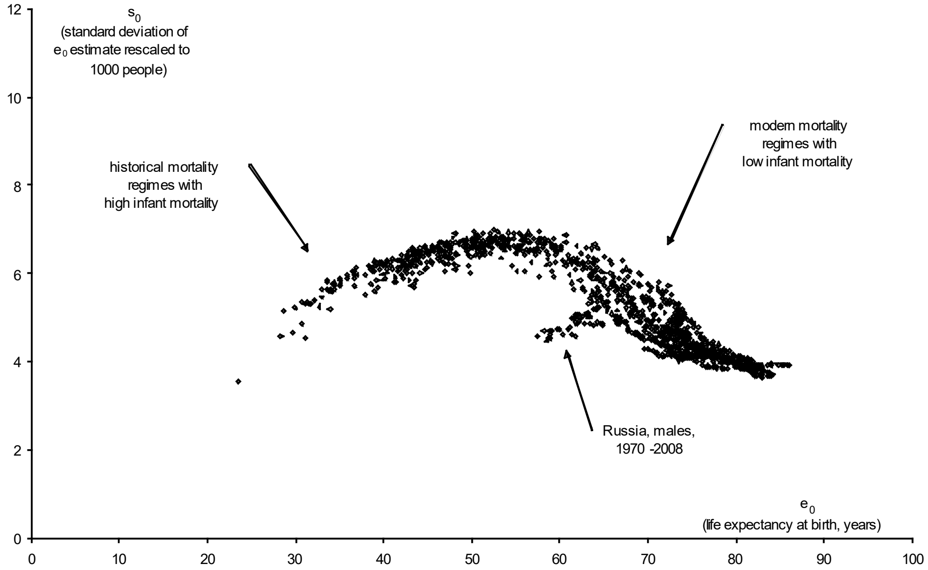

Figure 1. Association between standard errors of estimates and underlying theoretical values of life expectancy at birth for the stationary populations analyzed (one dot represents an average over 25,000 simulations)

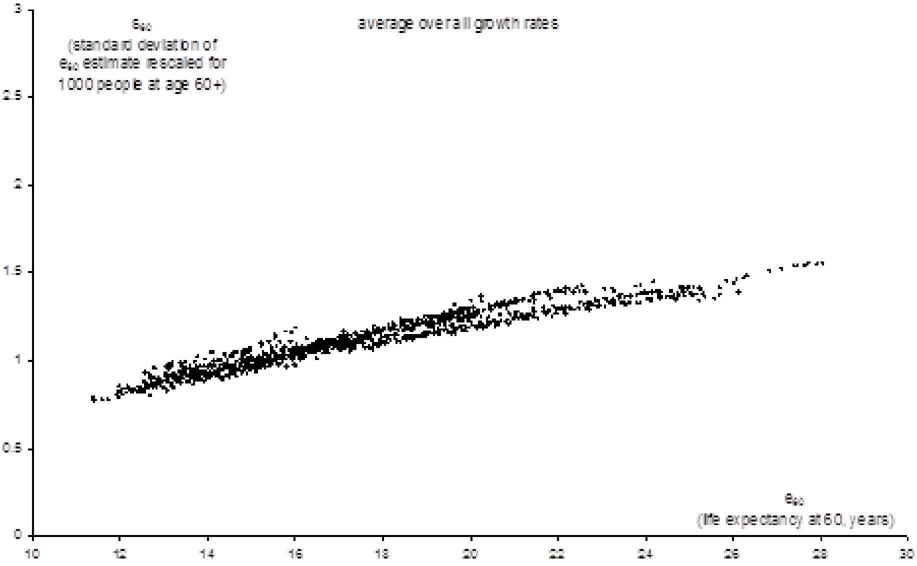

Figure 2. Association between standard errors of estimates and underlying theoretical values of life expectancy at 60 (one dot represents an average over 25,000 simulations).

where $\sigma_{err} = 0.1$ years (*r* is the stable population growth rate in percentage per annum: e_{60} for 1% growth rate, etc.)

The estimation bias of e_{60} is also correlated with the standard error of the estimation:

$$Bias_{60} = 0.366 \cdot SD_{60} + 0.0265 \cdot SD_{60}{}^{2} - 0.0094 \cdot SD_{60} \cdot r + err \qquad (11)$$

with $\sigma_{err} = 0.04$ years.

4.4 Normality of life expectancy estimate's distribution

Previous research (Silcocks et al. 2001; Eayres & Williams 2004; Williams et al. 2005) suggested that the distribution of estimates may be considered as approximately normal, which might simplify the practical use of standard errors of estimates (in applications such as the construction of confidence intervals, hypothesis testing, examining the significance of temporal or geographical variation of life expectancy, etc.) Strictly speaking the distribution of life expectancy estimates is not normal at any finite population size (see introductory formal considerations for explanations). For example, at 10,000 simulations, the Pearson test is powerful enough to reject normality of the simulated distribution of life expectancy even at a population of 100,000 people, when population growth is 2% per year. However, these are certain distribution percentiles rather than the normality of distributions as such, that are important for most applications. Estimates of selected percentiles derived from simulated distributions and from the corresponding normal distributions are presented in Appendix Tables A2 and A3. Percentiles obtained assuming the normality of estimates of life expectancy at birth or at age 60 are fairly close to those obtained directly from simulated distributions at a population size of 50,000 or more. Assuming normality for a population of 5,000 or less might be discouraged, unless the tested difference in life expectancies falls far beyond the confidence limits. When studying populations of an intermediate size between 5,000 and 50,000, one must be aware of the possible effects of deviation of the age composition of the population from the stationary age composition.

5. Illustrative examples

Simulation results illustrate that estimations of life expectancy for small populations may be associated with quite high standard errors and biases. Those must be taken into account both in designing the system of statistical observations and in interpreting geographical, temporal, and other variations of longevity obtained from small populations. Below we present several illustrations of this kind.

Case 1. Establishing confidence limits for life expectancy

Let life expectancy at birth be estimated at 86 years in a population of 20,000 people. What, roughly, would be the confidence limits for the actual life expectancy at the 95% confidence level, assuming stationary age composition? From Appendix Table A1, we may assess $s_0 \approx 3.9$ (years per 1,000 persons). Hence the standard error calculated for the actual population size would be $e_0 = 86 \pm 1.7$ (years). Assuming normality this yields $e_0 = 86 \pm 1.7$ years at a 95% confidence level.

Case 2. Examining the significance of life expectancy variation

Consider the hypothetical case of comparing life expectancy in two small populations. These populations may either represent two geographically or otherwise defined subpopulations of the total or the same population at two points in time. In the first case, we examine the significance of spatial or social variation in life expectancy, while in the second, we examine the significance of temporal variation. Suppose the two populations are characterized by the following indicators:

	Population 1	**Population 2**
Total population, people	20,000	50,000
Life expectancy at birth	86.0	83.5
Population at age 60 or more	5,930	15,629
Life expectancy at age 60	25.5	26.1

Then assume that the age composition of both populations is near stationary. Is the difference in life expectancy between the two populations significant (say, at the 5% significance level)?

To investigate the question above, we estimate standard errors of the estimates of life expectancy for the two populations. From Appendix Table A1 we may assess $s_0^{(1)} \approx 3.9$ (years per 1,000 persons) for the first population and $s_0^{(2)} \approx 3.9$ for the second population. Hence, standard errors calculated for the actual population sizes would be:

$$SD_0^{(1)} = 3.9 \Big/ \sqrt{\tfrac{20000}{1000}} = .9$$ and $$s_{60}^{(1)} \approx 1.5$$ (years).

Assuming the independence of the estimates for the two populations, we may compute the standard error of the difference between the estimates of life expectancy:

$$s_{60}^{(1)} \approx 1.5$$ (years).

Given the standard error and assuming normal distribution, the observed difference of 86.0-83.5=2.5 years yields *p*-value 1.6% (double-sided alternative) that is, *the difference is significant* at the 5% significance level. The two populations are different with respect to life expectancy at birth at the 95% confidence level.

Let us examine the significance of the difference in life expectancy at age 60. From Appendix Table A1 we obtain $s_{60}^{(1)} \approx 1.5$ and $SD_{60}^{(1)} = 1.5 \Big/ \sqrt{\tfrac{5930}{1000}} = 0.6$ for the two populations analyzed (years per 1,000 people of age 60 or more). Hence, standard errors estimated for the actual population sizes would be

$$SD_{60}^{(1)} = 1.5 \Big/ \sqrt{\tfrac{5930}{1000}} = 0.6$$ and $$SD_{60}^{(2)} = 1.4 \Big/ \sqrt{\tfrac{15629}{1000}} = 0.3$$ (years).

Assuming the independence of the estimates for the two populations, we may compute the standard error of the difference between the estimates of life expectancy:

$$SD_{60}^{(1)-(2)} = \sqrt{\left(SD_{60}^{(1)}\right)^2 + \left(SD_{60}^{(2)}\right)^2} = 0.7 \ \text{(years)}.$$

Given the standard error and assuming normal distribution, the observed difference of 26.1-25.5=0.6 years yields *p*-value 40% (double-sided alternative), that is, *the difference may not be considered significant* at the 5% significance level. The two populations do not differ significantly with respect to life expectancy at age 60.

Case 3. Minimal population size meeting the required level of estimation accuracy

Consider a situation where life expectancy at age 60 is estimated to be about 25 years, the proportion of the population aged 60 and more is 30%, and the age composition is stationary. Then suppose that the policymaker demands measurements of life expectancy at age 60 to be made at the regional level, with errors not exceeding 0.75 years at a 95% confidence level. What would the recommendation be about minimal population size for estimating the life expectancy at age 60 with the required accuracy? A difference of 0.75 years would not be statistically significant at the 95% confidence level at a standard error higher than $e_{60} = 25$ years (assuming normal distribution, double-sided hypothesis). For a stationary population with $e_{60} = 25$, eq. (9) implies that $s_{60} = 0.082 \cdot 25 - 0.001 \cdot 25^2 \approx 1.43$ years, that is, the critical threshold 0.38 of standard error may be reached at population size

$N_{60+} = \left(\frac{1.43}{0.38}\right)^2 = 14$ (thousand) at age 60 or higher, that is, at total population size $N = \frac{14}{0.3} \approx 46$ (thousand). Hence, estimation of life expectancy at 60 may be recommended for areas with at least 46,000 people.

6. General recommendations

We have shown that both the standard errors and the estimation bias become very high at a population size of around 5,000 or less. Additionally the distributions of standard errors deviate strongly from normality at such population sizes, which precludes building confidence limits and conducting other statistical analyses. Therefore estimating life expectancies for such populations must be discouraged.

Based on Appendix Table A1 and assuming that the standard error of the estimates of the life expectancy at birth is about one year or less, we may conclude that population exposure years should be about 15,000 people or more for a low-mortality population. To estimate life expectancy at 60 with a standard error of about 0.25 years, the population size should be about 100,000 or more for stationary populations, 65,000 for populations declining at 2%, and 250,000 for populations growing at 2% per annum. These rough estimates only outline how strict the requirements regarding population size could be to secure relatively accurate estimations.

We found the age composition of the population to be important for the accuracy of estimating life expectancy in small populations.

Precise assessments of standard errors and of minimal population size may vary considerably depending on actual population age composition and mortality schedules. Even the requirements for standard errors may vary from population to population, depending, for example, on observed spatial and social variation of mortality as well as on policy demands. In a country with high spatial diversity in life expectancy (e.g., Russia), even a low-precision estimate of life expectancy at the municipal level may reveal important regional differences, while for a country with more homogeneous regional mortality variation, like many western European countries, estimates must be conducted with higher precision, so that they reveal informative variations of mortality levels and not the random sample-size effects.

In most applications of standard errors, it is convenient to assume a normal distribution of the estimates. Our simulations indicate that such assumptions may safely be used starting from a population size of 50,000 people. For populations of 5,000 or less, such assumptions are not acceptable. In intermediate situations, normality assumptions may be used only as a rough approximation. More precise assessments, if necessary, may demand a detailed analysis and perhaps additional simulations tailored to the particular situation.

We do not find any advantages in using abridged life tables instead of unabridged ones even for a small population with many age groups containing no death observations. What is more, abridged life table calculations may lead to strong biases when the population age composition deviates from the stationary composition. Hence, it might well be advisable to use the unabridged life tables rather than the abridged ones when the population is not stationary.

Our simulation results show that procedures for the open age interval are crucial for the efficiency of life expectancy estimation. Although we found efficiency in our simple approach based on adjusting the open age interval in such a way that there is at least one death observed, more research on procedures for the open age interval could be important.

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6 Back to the Russian Roots

Introduction

Serhii Pyrozhkov

I met Sergei Scherbov in Moscow in the early 1980s, when he was working at the All-Union Scientific Research Institute for Systems Studies, the Russian branch of IIASA.[1] The Institute was elaborating economic policy strategies, including the creation of long-term programs for state development. Sergei travelled regularly to IIASA in Laxenburg to work at the Population Program, which was then headed by the world-famous American demographer, Nathan Keyfitz.

The Population Program has always held a respected position among IIASA's many scientific undertakings. Its leaders, Nathan Keyfitz and then Wolfgang Lutz, supported the participation of experts from Eastern Europe in their research projects. Sergei Yakovlevich was actively engaged in the development of methodology for probabilistic forecasting, application of aspects of multistate demography methods, and modelling of fertility and mortality rates using population data from the former USSR republics. As a demographer, I was very interested in his IIASA research and initiated discussions regarding possible cooperation.

I first visited IIASA in the late 1980s where Sergei was engaged on a long-term contract. Developments in the Population Program made a great impression on me and allowed me to determine a topic of joint research that was crucial for the population of Ukraine. It became evident to me that the Soviet government had done everything it could to conceal the true extent of the population losses resulting from the 1932–1933 famine in Ukraine. As a result, I decided to calculate those losses for myself, and Sergei supported me in this endeavor. We reconstructed the birth and death rates of the Ukrainian population for the intercensal period of 1926–1939. Our inherent assumption was that the famine of 1932–1933 had not taken place and that demographic development had evolved as a result of the demographic transition.

The result of our joint efforts was the recovery of age-specific fertility rates for the population of Ukraine from 1926 to 1939 (Lutz et al. 1990; Lutz et al. 1992). The research was based on the Coale-Trussull model for calculating the birth rate, which American researchers applied in 1974 (Coale & Trussell 1974). This work has led to further developments in estimating the Ukrainian population losses resulting from the catastrophes in the 1930s and 1940s. These were later summarized by the National Institute for Demographic Studies (Meslé & Vallin 2003, with contribution by Vladimir Shkolnikov, Serhii Pyrozhkov and Serguei Adamets).

Our cooperation continued in later years when, in the early 1990s, Sergei Yakovlevich went to work at the Population Research Centre at the University of Groningen in the Netherlands. There we forecast the working-age population of the former Soviet republics,

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[1] The Institute was established in 1976 as a branch of the International Institute for Applied Systems Analysis (IIASA) with the aim of providing scientific and methodological support for Soviet participation in IIASA. At the institute, there were no boundaries for discussion and practically no ideological censorship. The Institute was headed and permanently led by Academician Jermen Gvishiani for 17 years. At different times Yegor Gaidar, Peter Aven, Boris Berezovsky, Leonid Kantarovich, Mikhail Zurabov, Stanislav Shatalin, and other famous scientists and future statesmen of independent Russia worked at the Institute.

which allowed us to assess the labor potential of the population of Ukraine before the collapse of the Soviet Union.

Sergei earned deep respect and recognition among demographers both in Russia and former USSR republics for his numerous qualities: excellent command of modern methods of demographic analysis, a friendly (collaborative) attitude to colleagues, and a willingness to help solve complex problems in the demographic development of specific countries. His collaboration with Russian demographers was summarized in the key monograph "Demographic Trends and Patterns in the Soviet Union before 1991," published by IIASA in 1994. Wolfgang Lutz, together with Andrei Volkov a well-known demographer from Moscow, contributed significantly to this monograph, carrying out not only the overall editing of the book but also coauthoring some of its sections. The latest edition presents separate chapters on marriage and fertility issues, which Sergei prepared jointly with Wolfgang Lutz and Frans Willekens.

Other publications of Sergei, presented in this edition, demonstrate his broad scientific outlook, in particular his pioneering work on fertility tables broken down by nationality. A publication on the evolution of population mortality in the former USSR was prepared jointly by Leonid Darsky and coauthored with Yevgeny Andreev and Frans Willekens.

Sergei collaborated creatively with experts from the IIASA Population Program to evaluate the demographic aspects of changes in the Soviet pension system. This work was used to justify scenarios and produce forecasts of the age and sex structures of the populations of former USSR regions. Each of these research projects involved a substantial amount of background work, such as collection and evaluation of primary demographic information, making extensive calculations, and interpreting the results. It is thus not surprising that the development and annual publication of the Russian Demographic Data Sheet, which summarizes the indicators of Russia's demographic development for each calendar year, represents Sergei's lifetime work, and serves as a testament to his Russian origins.

Ukrainian demographers sincerely congratulate Sergei on his Jubilee, wish him creative longevity, and recall with deep gratitude the years of collaborative work in the name of the wonderful science of demography.

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Regional Fertility Trends in the Soviet Union[1]

Wolfgang Lutz and Sergei Scherbov

Stretching over nearly 10,000 kilometers from its western to its eastern border and encompassing very different peoples and cultures, the Soviet Union exhibits great regional heterogeneity in terms of population pat terns. The following note describes and analyzes heterogeneity in fertility in the USSR. We start with a description of the trends in fertility levels. We then look at age-specific fertility and find that various republics are at different stages in the transition from natural to controlled fertility. Lastly, we point out the implications these differential fertility patterns may have for the future ethnic and regional composition of the Soviet Union.

In 1987 the USSR population exceeded 281 million people (*Vestnik statistiki* N5 1987y). The national aver age crude birth rate was 19.4 per thousand and crude death rate 10.6 per thousand in 1984-85, implying an annual natural increase of 8.8 per thousand. In 1983, 72.6% of the total Soviet population lived in the European USSR and 27.4% lived in the Asian republics.

Data on regional fertility trends used in this analysis were published in *Vestnik statistiki* (see also Borisov 1974; Urlanis & Borisov 1984; Jones & Grupp 1987).

In the 1970s birth rates declined in most of the high-fertility republics and in both urban and rural populations. Thus, in almost all the republics the rate of natural increase was lower in 1980 than in 1970. However, the differences between the growth rates in the highest- and lowest-fertility republics increased even further to a factor of 22 between growth rates of 0.13% and 2.9% in 1980 in Latvia and Tadzhikistan, respectively.[2] Today, the Central Asian Republics, which contain one tenth of the total population, account for one third of the country's natural increase.

Figure 1 depicts trends in the level of the total fertility rate between 1959 and 1985 for the complete Soviet Union and for eight selected republics. In spite of very divergent paths of development in the republics, the aggregate fertility levels in the complete Soviet Union look very stable around a TFR of 2.4 to 2.6. The only features worth noting are a slight decline between 1959 and 1965 and a very weak increase after 1982. This recent increase might be explained in part by a change in weights toward the high-fertility republics, but it might also reflect some real change in behavior. In the Asian republics the TFR ranges between 4 and 6; while in the Baltic republics, the Ukraine, Belorussia and in the Russian Republic, fertility now is around replacement level or even somewhat below. These regional differences are explained by social, ethnic and other peculiarities of different segments of the USSR population.

Three fertility patterns

With respect to their trends over time, the Soviet republics might be classified into three categories: (1) the high natural fertility republics; (2) the middle, transitional-fertility republics; and (3) the low, controlled-fertility republics.

Uzbekistan, Azerbaydzhan, Turkmenistan, and Tadzhikistan fall into the first category. Tadzhikistan, a relatively small republic bordering Afghanistan with currently the highest

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[2] See: The USSR National Economy in 1980 (1980), Moscow, p. 32-33.

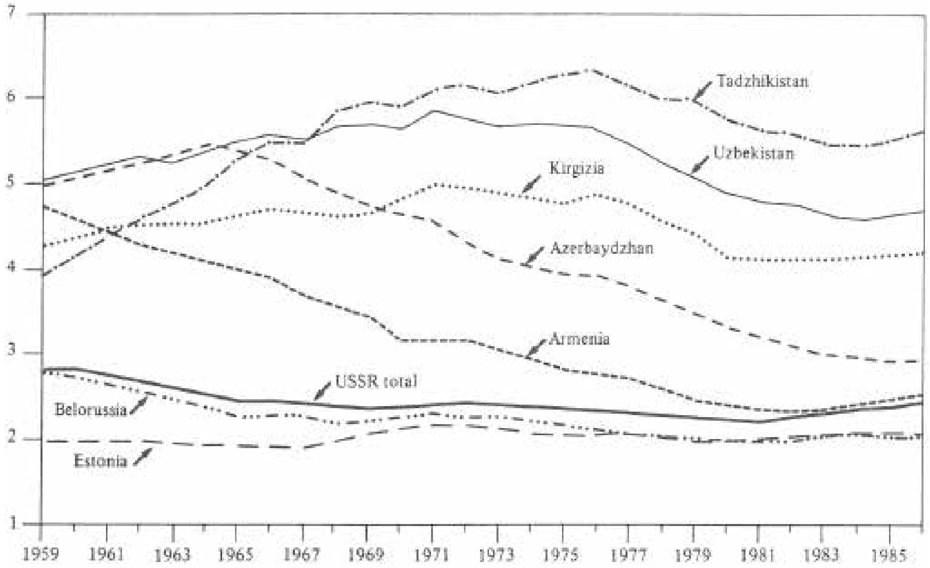

Figure 1. Total fertility rates in selected Soviet republics, 1959-1986.

level of fertility (a TFR of 5.7 in 1986), shows clearly increasing fertility levels between 1959 and 1976, and only a slight decline thereafter. As in many high-fertility countries the reason for such a marked fertility increase lies most probably in a decreasing incidence of sterility and a shortening of birth intervals owing to changes in traditional behavior. The other three republics in this category show similar trends, with different turning points from increase to decline. In Azerbaydzhan fertility increased until 1964 and then entered a steep and lasting decline. In Uzbekistan fertility levels peaked around 1970 and declined thereafter. Turkmenistan, which is not shown on the graph, followed a line of development almost identical to that in Uzbekistan, only at a slightly lower level of fertility.

The second group of republics includes Armenia, Kazakhstan, and Moldavia and shows steep fertility declines between 1959 and the late 1960s, followed by slower declines or even stability. These republics seem more advanced in their demographic transition than the republics in the first category, and we seem to have caught the tail of the fertility transition in the early 1960s. In Kazakhstan the pattern might be more complex because of the great heterogeneity of the population consisting of high-fertility Kazakhs and other ethnic groups with low fertility (about 50% of the population).

The third, low-fertility category consists of republics that have already passed through the secular fertility decline and show only some post-transitional fluctuations. In Estonia (shown in *Figure 1*), which is one of the lowest-fertility republics in the Soviet Union, we note a relatively steep fertility increase between 1967 and 1971. We could speculate that this was a phenomenon similar to the baby boom in most Western countries. The pattern in Latvia is similar to that in Estonia. Lithuania followed the same trend at a somewhat higher level of fertility. The very populous Ukraine showed a slight decline at an already low fertility level until 1965 and almost no change thereafter – similar to the trend in the Russian Republic, which is by far the largest republic in terms of territory and people.

Applying the paradigm of demographic transition to the fertility patterns in the Soviet republics observed between 1959 and 1986 and discussed above, we may interpret the different categories of republics as representing different phases of a transition process from natural to controlled fertility, with Tadzhikistan and Uzbekistan the latest to follow this trend. We investigate this point further by looking at age-specific fertility rates in selected republics and by calculating the index of family limitation.

Age-specific fertility rates

Figure 2 gives the trends in age-specific fertility rates for Estonia. The trends are generally rather smooth. The greatest discontinuity was the almost 30% fertility increase for women in the prime childbearing group, age 20-25, between 1967 and 1972. After 1972 the rate remained stable at the new high level. Although we do not know the reason for this phenomenon, we may assume that it. had to do with changes in marriages pattern because the fertility rate of women aged 15-20 also increased substantially; this increase, however, stretched out over a much longer period. In other groups the fertility increase was a short-term phenomenon visible also in the age groups 25-30 and 30-35. Beyond age 30 fertility declined slowly over the whole period. This is a clear indication of a controlled-fertility regime.

In *Figure 3* we see the trends in age-specific fertility rates for Uzbekistan, a high-fertility republic. The fertility of women between ages 20 and 30 increased from 1959 to 1976 and then slowly declined. For the next age group, 30-35, the increase lasted only until 1969. For women aged 35·-40 the increase was less pronounced, but the decrease after 1970 was very strong. Women above age 40 show declining trends since the early 1960s.

What explains the fertility increase for younger women followed by a decline? We suggested above that the initial increase in already high-fertility republics was not due to an increase in desired family size, but due rather to an increase in the biological potential for childbearing. We may assume that within a natural-fertility regime increases in average fertility levels can be explained by changes in the proximate fertility determinants: fecundability, breastfeeding and the exposure to intercourse. It seems safe to assume that increasing educational standards together with improvements in health care in the high-fertility republics resulted in lower sterility rates and higher monthly probabilities of conception. A reduction in the percentage of women breastfeeding, and in duration of

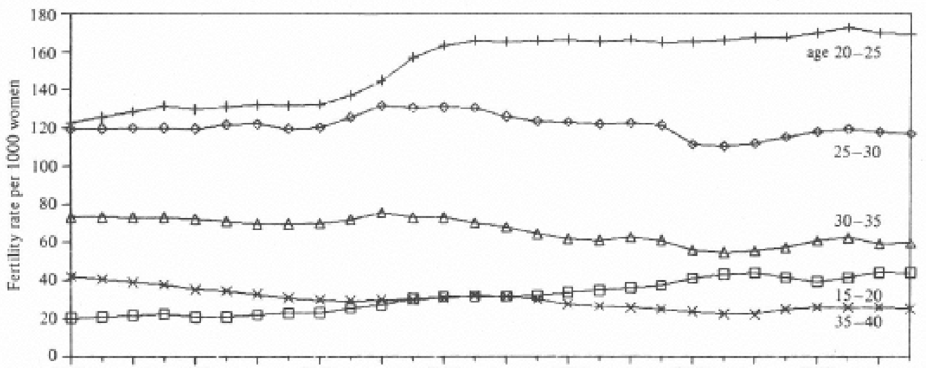

Figure 2. Age-specific fertility rates in Estonia, 1959-1985.

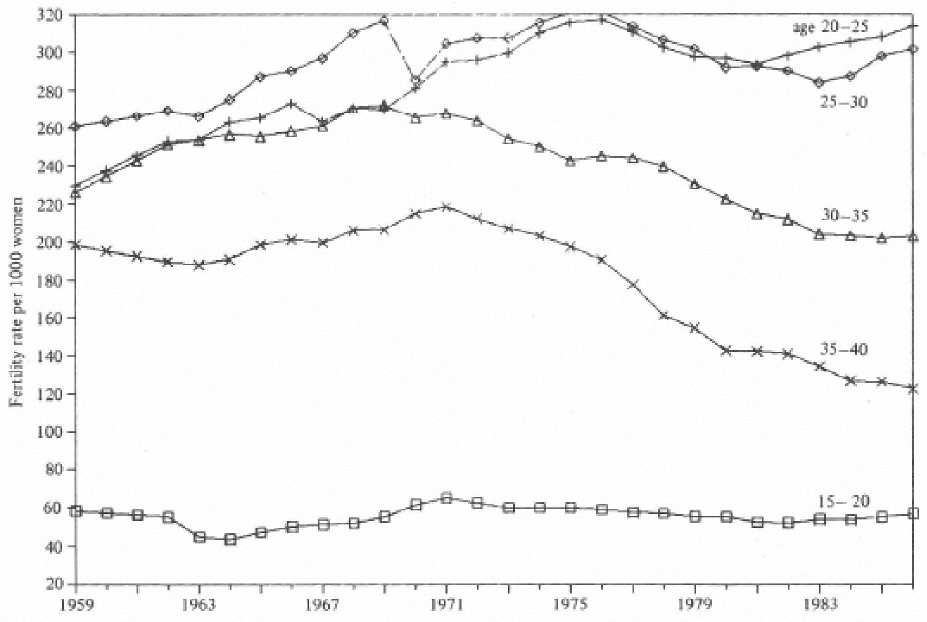

Figure 3. Age-specific fertility rates in Uzbekistan, 1959-1985.

breastfeeding, is another possible explanation for increased fertility levels. Fertility declines at higher ages, however, indicate the advent of fertility control, where women consciously limit family size when they already have the number of children they want.

Transition to controlled fertility

The change from natural to controlled fertility can best be illustrated by the change in the shape of age-specific fertility rates. If the curve is concave (to the origin) at higher ages, fertility is natural with older women still demonstrating relatively high fertility. If the curve is convex, this indicates controlled fertility because older women tend to have lower fertility in response to higher numbers of children. This is true regardless of the level of fertility.

Figure 4 gives age-specific fertility curves for Uzbekistan in 1959 and in 1985. In 1959 the curve was clearly concave. In 1985 the level of fertility was still high, but the shape had already changed dramatically and clearly indicated controlled fertility. It had about the same shape as the controlled-fertility curves in Estonia, Belorussia , and the average of the whole Soviet Union in 1985.

Coale and Trussell (1974) suggested a quantitative way to assess the degree of fertility control in a population. Among others, their model is designed to estimate a parameter m of fertility control, which measures the degree of deviation from natural fertility. We have applied the Coale-Trussell model to overall age-specific fertility rates from 1959 to 1986 (with the exception of a few years that were interpolated). This model was also used to convert empirical five-year age groups into one year age groups. In almost all cases the fit was good. But for a few high-fertility republics we found that observed fertility rates in older age groups were higher than those estimated by the Coale-Trussell naturalfertility model. This might be a clue to the existence of a somewhat different standard natural-fertility schedule in Soviet Asia.

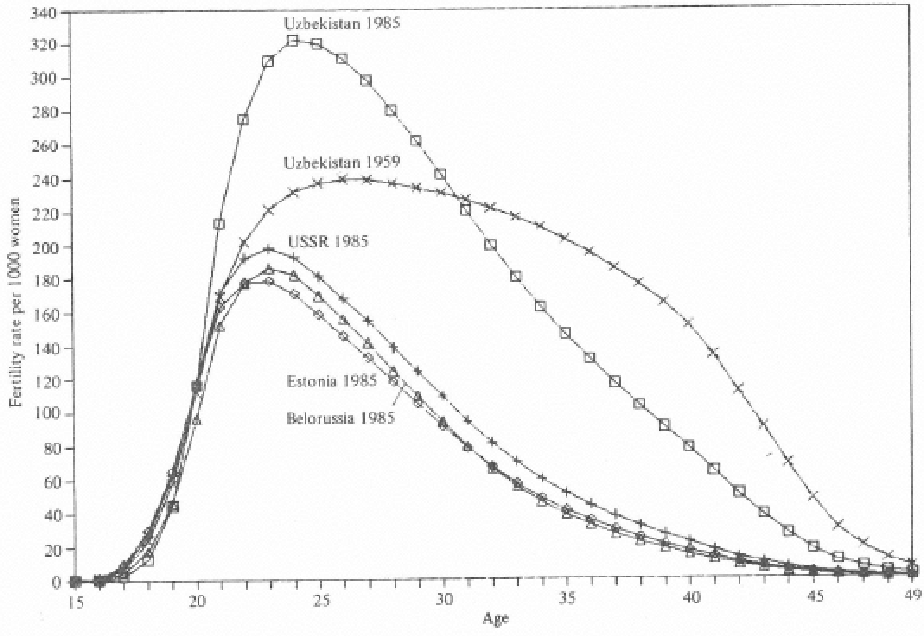

Figure 4. Age patterns of fertility in selected republics and years.

The degree of deviation from natural fertility measured by *m* is given in *Figure 5* for three selected republics and the Soviet Union as a whole. Values of *m* close to 0 imply natural fertility. The shift to controlled fertility is gradual and takes place somewhere between *m* = 0.5 and *m* = 0.8. Thus, in Uzbekistan fertility proved to be virtually uncontrolled until the late 1970s. By 1985 Uzbekistan had reached a level of fertility control that is comparable to the highly advanced republics in the late 1960s. Al though this index gives only a crude indication of a fertility regime, we clearly see the structural change for Uzbekistan and the further trend toward higher control in the European republics and the Soviet Union as a whole.

Implications for population diversity

This analysis of regional fertility trends in the Soviet Un ion over the last 28 years leads us to the general conclusion that the fertility transition is at least well under way in each of the Soviet republics and has already long been finished in others. It is quite likely that at some time in the future all republics will have low-fertility regimes and regional heterogeneity will be greatly reduced. Up to that point, however, regional fertility differentials will have considerable influence on the regional and therefore also national and ethnic composition of the Soviet Union. Nations and republics with low present fertility will inevitably become relatively smaller, while the Asian republics that have only recently started their fertility decline will make up much larger fractions of the Soviet population in the future.

To illustrate the effects of differential fertility levels in the USSR and in general, we did a rough projection exercise with the population composition of the Soviet. Union up to 2030. Being a rough model, it cannot be considered a serious population projection. Column 1 in *Table 1* shows the empirical distribution of the total Soviet population over the 15 republics in 1970. The second and third columns show the projected distributions in 2000 and 2030

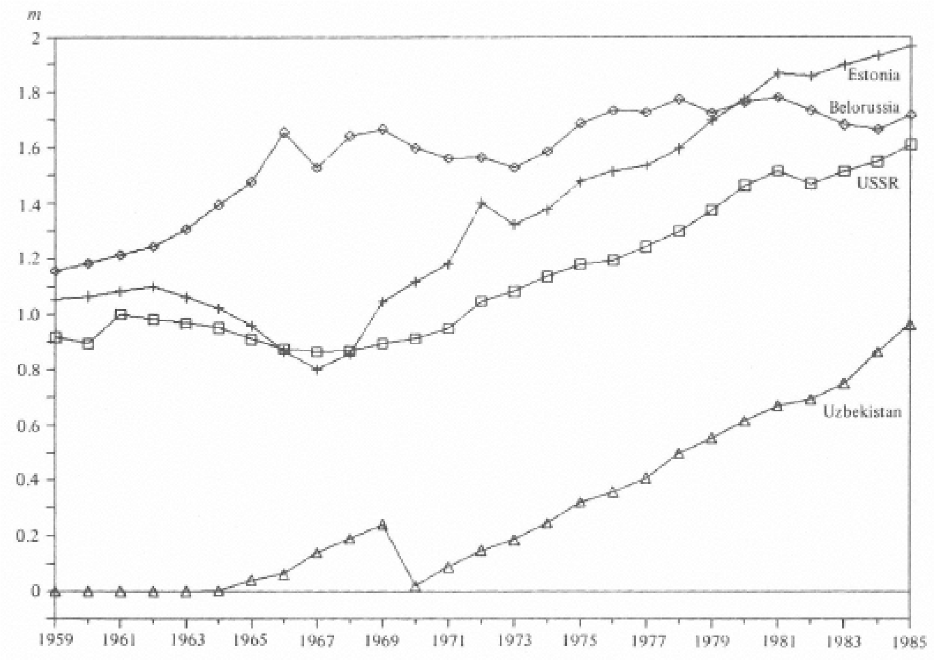

Figure 5. Index of family limitation m in selected republics, 1959-1985.

using the following rather crude assumptions: mortality is constant, internal migration rates are fixed as they were in 1970, and fertility remains stable around the 1980- 1986 level in each republic. This model clearly shows that a persistence of differential fertility levels over the next decades would result in considerable changes of the population distribution, with the Asian republics increasing their relative weight. But assumed future differences in fertility levels are only part of the reason for these shifts, another reason being the existing age-distributional difference produced by past fertility patterns, and the consequent momentum of population growth in the republics with recent high fertility levels.

From *Table 1* we see that Uzbekistan will gain most at the expense of mainly the Russian Republic and the Ukraine. The mean age of the population has a tendency to increase in all republics, but the increase will be higher in the European parts than in the Asian republics, resulting in a widening of the age gap. For instance, the differences between the mean ages of the populations in the most extreme cases – Latvia and Tadzhikistan – will increase from 12.1 years (35.7 as compared to 23.6) in 1970 to 15.3 years (39.3 as compared to 24.0) in 2030. This implies that the problem of aging will affect different parts of the Soviet Union in very different ways.

The subject of Soviet fertility trends and their implications for the future deserves a much more extensive and sophisticated analysis than could be given in this short note. In the coming months at IIASA these questions will be studied in more depth. But this brief introduction already indicates that the demographic experience of the Soviet can contribute much to the understanding of secular fertility trends. In turn demo graphic theory can be usefully applied to point out the likely future implications of differential fertility for the regional and ethnic composition of the population and its aging process, together with the economic and social issues likely to arise from these changes.

Table 1. Distribution of Soviet population by republic in 1970 and as calculated for 2000 and 2030 under the assumptions of constant 1980-1986 fertility, mortality and migration levels.

	1970			2000		2030		1970-2030
Republic	Population (in 'OOOs)	Proportion of USSR	Mean age	Proportion of USSR	Mean age	Proportion of USSR	Mean age	Gain or loss (%)
RSFSR	130079	53.8	32.0	50.4	37.4	45.8	39.3	-8.0
Ukraine	47126	19.4	33.6	17.7	37.8	15.8	39.1	-3.6
Belorussia	9002	3.7	31.8	3.5	36.8	3.3	39.1	-0.4
Uzbekistan	11799	4.8	24.5	7.1	25.3	10.6	26.0	5.8
Kazakhstan	13008	5.3	26.6	6.2	31.2	6.7	33.l	1.4
Georgia	4686	1.9	30.8	1.7	36.0	1.4	38.2	-0.5
Azerbaydzhan	5117	2.1	24.8	2.6	28.8	3.2	31.3	1.1
Lithuania	3128	1.2	32.9	1.2	36.7	1.1	38.8	-0.1
Moldavia	3568	1.4	29.5	1.4	34.4	1.4	36.4	0.0
Latvia	2 364	0.9	35.7	0.9	38.3	0.8	39.3	-0.1
Kirgizia	2932	1.2	25.9	1.5	27.7	1.9	28.8	0.7
Tadzhikistan	2899	1.2	23.6	1.9	23.8	3.2	24.0	2.0
Armenia	2 491	1.0	26.1	1.2	32.2	1.3	36.2	0.3
Turkmenistan	2158	0.8	24.0	1.3	25.0	2.1	25.6	1.3
Estonia	1356	0.5	35.3	0.6	35.2	0.6	37.6	0.1
USSR[a]	241720	100.0	32.2	100.0	35.2	100.0	36.0	

[a] Total population is estimated to be 305.747 million in 2000, and 353.900 million in 2030.

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Marital and Fertility Careers of Soviet Women. A life Table Analysis[1]

Frans Willekens and Sergei Scherbov

1. Introduction

In most regions of the world, social change is accompanied sooner or later by a significant change in family life. The traditional functions of the family, namely economic, social, and emotional support to members, are eroding. In a 'modern' society, the individual has the choice to obtain economic, social, and even emotional support from relationships and institutions other than the family. Although most people rely on the family for many of the traditional functions, a growing number of people do not choose a family-oriented lifestyle. As a consequence, new trends have become manifest:

- people marry later and some do not marry at all;
- marriages which are dissolved by age 50 are more likely to be dissolved by divorce than by death of one partner;
- the proportion of married people that are committed to a single family for the entire lifetime is decreasing;
- women have fewer children and give birth at higher ages; the lives of women are structured less around childbearing; women increasingly derive status from activities other than raising children;
- marriage and fertility are tied less than they used to; the proportion of children born outside of legal marriage is on the increase in western societies.

In addition to these trends, mortality decline has an effect of its own. Because of the increased life expectancy, a woman may expect to live longer after she completes raising children. Consequently, the share of child-bearing and child-raising years in the total lifetime is decreasing, not only because of a decline in fertility, but also because of a decline in adult mortality.

These trends are manifest in many western countries, as well as the Soviet Union. There is however a very significant difference. In the Soviet Union, marriage is universal and Soviets tend to marry much younger than their West European counterparts. The proportion of women who never marry is between 1 and 2 percent. The Socio Demographic Survey of 1985 revealed that of the girls born in 1940-44, 29.7 percent entered first marriage by the age of 20 (State Committee for Statistics 1988, p.200); half of the 1942 cohort was married by 22.4 (Volkov 1986, p.125). The proportion marrying at an early age is increasing. Of those born in 1950-54, 32.1 percent married before their 20th birthday (median age 21.5), and so did 34.0 percent of the 1960-64 cohort. Housing shortages, prejudices against cohabitation and modern contraceptives, inadequate sexual education, and lack of effective contraceptives are the main reasons for early marriage. The European (August 31-September 2, 1990) recently reported that as many as half of the brides in some parts of the country are pregnant when they marry. Childlessness is very small in the Soviet

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Union. The proportion childless remains stable between 6 to 8 percent, and childlessness is mainly due to natural infecundity which is being estimated at 5 percent.

Fertility decline has been a consequence of the decline in births of high parity. The period total fertility rate (TFR) is about 2.45. The Socio-Demographic Survey of 1985 showed that 11.8 percent of the married women between ages 18 and 59 have three or more children. Darsky and Scherbov (1990) calculated from the survey of 1985 that, of the women who married in 1970-74, 95.2 percent had at least one child. They also found that of women who gave birth during the 1970-74 period, 24.6 percent had three or more children. These general figures mask very important regional differences. The fertility transition was completed as early as 1959 in the European part (Coale et al. 1979; Jones & Grupp 1987). It is beginning only now in the Asian republics. For instance, the proportion of women who gave birth in 1970-74, and who had three or more children in 1985, was 12.7 percent among Russians and 89.1 percent among Uzbeks (Darsky & Scherbov 1990).

Although marriage is universal, the marriage institution is decreasing in significance. The divorce rate (number of divorces per 1,000 married couples) increased from 5.3 in 1958-59 to 11.5 in 1969-70 and further to 15.2 in 1978-79 (Anon 1985, p.359). In 1984-85, it is 14.1 (State Committee for Statistics 1988, p.208); in 1988, it is calculated to be 13.9 percent, amounting to about one million divorces. Experts attribute the high divorce rate to early and forced marriages. Because of reasons given above, many young couples rush into marriage when they barely know each other and are unprepared for the responsibilities. Divorces are easily obtained provided children are not involved. The couple fill in a few forms, pay a fee of 100 rubles (almost half a month's salary) and go their separate ways. Not all divorces can be attributed to dissatisfaction with the partner. In large cities such as Moscow and Leningrad, the number of divorces are inflated by so-called paper marriages, by which residents marry people keen to move to these places, but who otherwise do not meet the requirements of the residential permit system, which was established to control the number of inhabitants. Remarriages are becoming more important. In 1978, remarriages constituted 14.3 percent of all marriages; in 1988 it was 22.7 percent (State Committee for Statistics 1989a, p.134 and 154).

The purpose of this paper is to explore the changes in nuptiality and fertility in the Soviet Union, and the associated changes in women's lives. Multistate life table analysis is introduced to generate complete marital and fertility histories (biographies) of women as they pass through reproductive ages (16-50). The biographies are synthetic biographies since they are not completely observed but inferred from the available data on nuptiality and fertility. The life table is a method to determine the biography that is consistent with a set of vital rates and to assess the impact of changes in these rates. The multistate life table has become a useful technique in family demography (see. e.g., Schoen et al. 1985; Zeng 1986; Zeng 1990; Bongaarts 1987; Espenshade 1987; Willekens 1987; Keyfitz 1988) Zeng Yi, 1986, 1990; . In addition to the multistate life table method, the theory of staging or sequential processes is used to describe marital and fertility careers. This theory focuses on the occurrence and timing of chains of events (Chiang 1984; Willekens 1990). Cohort data are used when available.

The first section of the paper presents the marital biographies women would experience if the rates of marital change observed in 1988 would prevail. Data limitations prevent the use of cohort data and a comparative analysis over time and space. The second section describes fertility histories. Two birth cohorts are distinguished: 1940-44 and 1950-54. The combination of the marital and fertility histories to picture the complete life course of Soviet women is not pursued because the marital careers are based on period data, whereas cohort data are used to reconstruct the fertility careers. Prospective biographic indicators are dependent not only on patterns of marital change and fertility, but also on mortality. Since marital and fertility careers are estimated up to age 50, the effect of mortality is small. The USSR life table for 1986-87 indicates that 95.1 percent of females aged 16 survive to age 50 (State Committee for Statistics 1989b, p.147).

2. Marital Career

In 1989, the State Committee for Statistics published the number of marriages by age, sex, and marital status prior to marriage, as well as the number of divorces by age (5-year age groups), and sex. The data are shown in Table A.1. They are derived from the marriage certificates issued in 1988. For a description of the Soviet vital registration system, the reader may consult Jones and Grupp (1987, pp.38–45).

To construct the marital history of women from these data, rates of marital change must be estimated. The 1989 All Union Census of Population provides data on population by age, sex, and marital status as of 1st January 1989. The marital status composition of the female population is shown in Figure 2.1 and the figures are given in Table A.2. The data are considered adequate estimates of the population at risk. Occurrence-exposure rates by single years of age are estimated in two steps. First, the number of marital transitions and the marital composition of the population by single years of age are estimated from the 5-year data using natural spline interpolation. Second, the occurrence-exposure rates are obtained by dividing the number of marital events by the population at risk. Rates of widowhood are not available from these data. It is assumed that the male mortality rate is independent of marital status and that the age difference between bride and groom at time of marriage is negligible (in fact, the age difference is about two years). Under these conditions, the age-specific rates of widowhood of females are equal to the age-specific male mortality rates. The occurrence-exposure rates are shown in Table A.3.

Two types of life table analyses are carried out. First, the multistate marital status life table is prepared. The table shows, for various ages, the probabilities of being of a given marital status, the probabilities of marital change, and the expected sojourn time in each

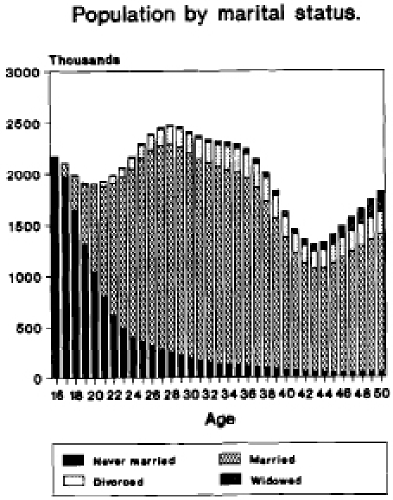

Figure 2.1

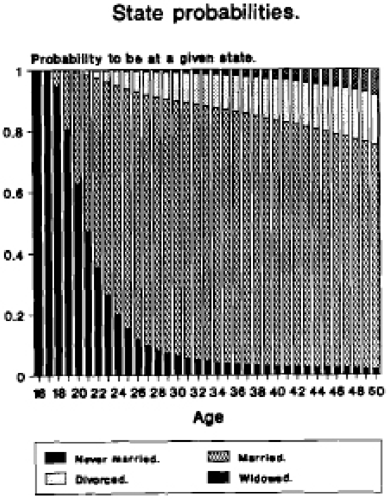

Figure 2.2

marital status. Four marital states are distinguished: never married, married, divorced and widowed. Second, order-specific marital states are considered. A distinction is made between first marriage, second marriage, and higher-order marriages; first marriage dissolution, second dissolution, etc. The marital life course is viewed as a staging process. A stage is a period or episode of life, characterized by the marital state occupied and the number of times one entered the marital state (Chiang 1984, Chapter 12; Willekens 1988). It is stressed that the marital career is studied up to age 50. Prospective indicators such as the expected duration of marriage, are for the period up to (but not including) age 50.

Life table analysis shows a probability of ever marrying (by age 50) of 98.0 percent. The figure is high if compared to that of other European countries. At age 25, 78.5 percent of women are married, according to the life table analysis. The marriage of some (6.2 percent) has already been dissolved at that age, mainly because of divorce (5.9 percent). Figure 2.2 shows probabilities of occupying given marital states for various ages. The life table estimates are very close to the census data on those aged 25 (78.5 percent are married, 5.6 percent are divorced, and 0.5 percent are widowed). An early divorce has a significant impact on a woman's marital biography. For instance, the probability of being divorced at the age of 30 is much higher for women who are divorced at an earlier age, e.g. 20. The probability that a 20 year-old will be divorced at age 30 is 23.1 percent if that person was already divorced at age 20, and 10.8 percent if that person was married at age 20. In other words, a woman is much more likely to be married at age 30 if she has not been divorced before. The difference reflects the differences in the age profiles of marriage and remarriage. The impact of an early divorce on marital status diminishes as the person gets older. The marital status of a person at age 40 is not very much affected by the marital status at age 20. The probability of being divorced at 40 is 19 percent for those who are divorced at 20, and 14 percent for those who are married at that age. The finding that a person 'forgets his/her past' can be attributed to the Markovian assumption underlying the multistate life-table model used in this paper. The marital state probabilities by age and marital status at age 20 are shown in Table A.4.

The probability that marriage ends in divorce before age 50 is 36.7 percent. The probability that marriage ends in widowhood is much smaller, since older women are excluded from our analysis. The probability that a woman celebrates her 50th birthday in widowhood is 8.3 percent.

The probability measures of the marital life course may be augmented by duration measures. How long does a woman spend in each of the marital states, provided that she experiences the rates of marital change observed in the USSR in 1988? The sojourn times are determined by two parallel processes. The first process is marital change; the second is mortality. The effect of mortality is small except at high ages and is not considered in this paper.

The marital biography of a woman may be described by the timing of marital change and the sequence of marital states occupied. Each sojourn in a marital state is a stage of marital life. Multistate life table analysis shows that women marry at age 22.4, on average. However, not all women marry. Those who marry before age 50, do so for the first time at age 21.8, on average. The multistate life table measure is inflated because 2 percent of the women never marry. The mean age at first marriage observed in the 1988 population was 22.39 (calculated from single-year age data interpolated from 5-year data on marriages; State Committee for Statistics 1989a). The difference is due to the age composition of the population. Of the 34 years that separate ages 16 and 50, 24.0 years are spent in marriage. The sojourn time in marriage is influenced by the marital history. A person who is married at age 20 may expect to spend more time in marriage beyond that age than a person who is not married yet or who is already divorced (25.6 years versus 21.8 and 20.7 years). As marital change becomes less likely at higher ages, the marital status one occupies becomes a better predictor of the expected sojourn time in each marital state as age increases. For instance, the number of years a woman of age 40 may expect to spend in each marital state is very much determined by her marital status at that age. If she is married, she probably stays married and consequently 9.2 years of the ten that separates her from her 50th birthday are spent in marriage, on average. If she is divorced however, she may look forward to only 1.6 years in married life. The time in marriage is even less if the woman is widowed at age 40. Table A.5 shows the expected sojourn time in each marital state by age and marital status at each age.

We may study the marriage pattern by viewing the marital career as a staging process. Two events are distinguished: marriage and marriage dissolution. The occurrence of the event initiates a new stage, and a sequence of stages defines a career. Figure 2.3 exhibits the time spent in each of the stages by women with different marital careers. A woman who experiences only one event by the age of 50 is married at that age. Her career is shown at the left. As the number of events increases, the time spent in each stage becomes smaller.

The data do not permit an investigation of how cultural and economic changes are affecting the marital biographies of women. We know that the divorce rate started to increase in the 1960s from a low of 5.3 percent at the end of the 1950s to 11.5 percent at the end of the 1960s. Remarriages have become much more common. The proportion of marriages that are remarriages increased from 14 percent at the end of the 1970s to 23 percent at the end of the 1980s. Part of the increase can be attributed to the increased prevalence of divorces (6.6 percent of all women in the 1979 census and 7.6 percent in the 1989 census). The rate at which divorced women remarry in a year increased too, however, from 3.5 percent in 1979 to 5.9 percent in 1988 (calculated from data published in State Committee for Statistics 1988; State Committee for Statistics 1989a). The specific reasons for these changes remain unknown although they are likely to be related to the changing status of women. Declining adult male mortality postpones the widowhood stage in a

Time spent in marital stages for different marital careers.

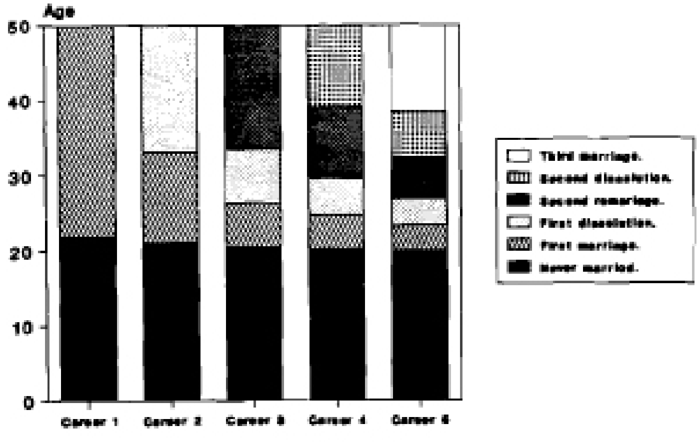

Figure 2.3

woman's life. The probability of ending marital life in widowhood and the average number of years spent in widowhood is not affected much by mortality trends, since adult mortality is also declining for women.

3. Fertility Career

The period TFR in the Soviet Union is about 2.45, which means that on average, a woman has two to three children during her lifetime. The TFR remains stable for many years. Not all women have a fertility career. Between 6 to 8 percent of the women remain childless. Natural sterility amounts to about 5 percent. Marriage is not a limiting factor since the proportion of women who do not marry is very small (1 to 2 percent). Almost all married women who are able to have children do so.

The fertility careers of women will be studied using cohort data. For this purpose, we used data on the number of children ever born to women of different ages and parity.[2] The data by cohort were reconstructed. In order to study the fertility careers of women by birth cohort, the data were transformed into occurrence-exposure rates. The transformation consists of two steps. First, the number of children ever born by birth order to women of a given cohort are estimated for single years of age from five-year age data. Second, rates at which women of a given parity and age have an additional child (occurrence-exposure rates) are estimated from the number of children ever born data, assuming that fertility is the outcome of a Markov process. The occurrence-exposure rates are the parameters of staging processes, underlying the fertility careers. The rates are given in Appendices B.1 and B.2. The rates serve an input to estimate the density distribution of children born by birth order. The densities for the 1940-44 and the 1950-54 cohorts are shown in Figure 3.1. The

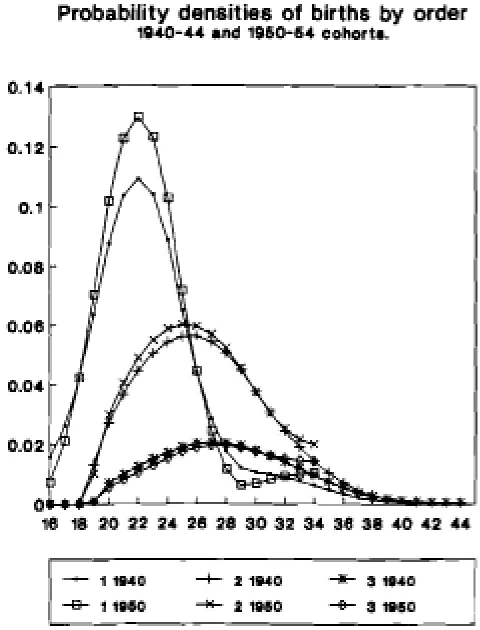

Figure 3.1

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[2] The data was brought to IIASA by A. Vishnevsky, and prepared by A. Vishnevsky and A. Anichkin.

figure demonstrates the increase in first and second births, and the decline in higher-order births.

In this section, the fertility career is studied irrespective of the marital career. The marital career described in the previous section is based on period rates of marital change observed in 1988. The fertility rates used in this section are cohort rates for the 1940-44 and the 1950-54 birth cohorts.

The fertility careers of women start relatively early. Fertility before age 20 accounts for about 10 percent of total fertility and the mean age at first childbirth is about 23. These figures do not change much as fertility declines, due to continued early marriage. Fertility decline in the Soviet Union is therefore predominantly affected by a decline in higher-order births.

Figures 3.2 and 3.3 show the parity distribution of women, born in different periods, at various ages. Women born in 1940-44 had on average 2.05 children by the end of the reproductive career. Women with children had 2.34 children on average. Life table analysis shows that about 12 percent remained childless, 23 percent had one child, 39 percent had two children, and 25 percent had three or more children. The proportion with six or more children was as high as 6 percent. Large families are situated in Asian republics with high fertility nationalities [TFR: Tajiks 6.9; Turkmen 6.5; Kirghiz 6.5; Uzbeks 6.4; Kazakhs 5.6 (Darsky & Scherbov 1995)]. Women of more recent cohorts are as likely to have children as women of older generations. The age at which women have their first child is decreasing, probably due to increased sexual activity at younger ages, and the lack of adequate knowledge on and availability of contraceptives.

Childbearing is generally completed by age 37. The TFR of the 1940-44 cohort at age 37 is 2.00. Eight percent of the children are born before age 20, 46 percent before 25, 77 percent before 30, and 94 percent before 35. The fertility careers of most women extend over a period of 15 years between the ages 20 and 35. At age 20, 15 percent of the women have at least one child. The percentage of women with at least one child at higher ages are: 55 percent at age 24, 65 percent at age 25, 82 percent at age 30, and 86 percent at age 35. At age 30, one-third of the women have exactly one child and another third have two

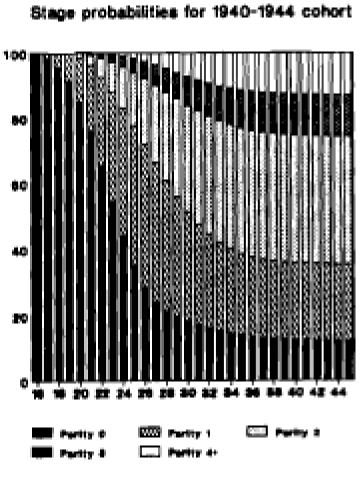

Figure 3.2

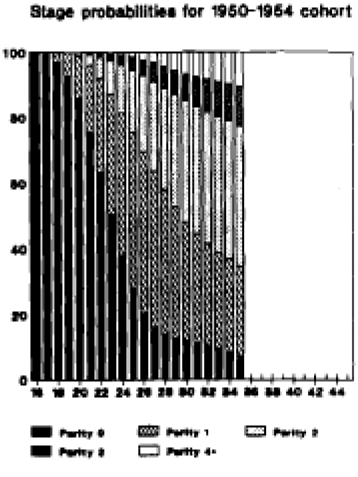

Figure 3.3

children. The proportion of childless women at that age is 18 percent. Sixteen percent have three or more children. The distribution of completed family size has been given before. It is the distribution of mothers aged 45 by the number of children born (mortality is assumed to be absent).

The mean age of mothers at childbirth is given in Appendices B.3 and B.4. The mean ages shown are the ages at which women who reached the age shown in the row, had their first, second, etc., child. For instance, a woman born in 1940-44 with at least one child at age 30, has the first child at age 22.7, on average; women with at least two children at age 30 have the second child at age 25.2, etc. The mean age at which women who completed their fertility had their first child is 23.4 years. The second child is born at age 27.2, on average.

Appendices B.5 and B.6 provide estimates of average birth intervals. For calculating birth intervals, we may of course not take the difference between mean ages, because not all women of a given parity experience an additional birth (see Feichtinger 1987, p.97).

The interval between two consecutive births depends on the completed parity. Let $x_{i,j}$ denote the mean age at the i-th birth of those women whose completed parity is j $(j = i, i + 1, i + 2, \ldots)$. Note that the $x_{i,j}$ values are not observed, but estimated from the parameters of the fertility process, i.e. the age- and parity-specific fertility intensities (occurrenceexposure rates). The estimates are approximations and should be treated with caution. For instance, the values of $x_{1,2}$ are obtained by summation of the densities of second births, weighted by the difference between the age at second birth and the average age at which these women had their first child. It is equivalent to the sum of the densities of the second child, weighted by the average age of the first child at the time of birth of the second child. The method is an improvement on the technique suggested by Ryder (Wunsch & Termote 1978, p.170). Ryder approximates the birth interval by the difference between the mean ages at two consecutive childbirths, divided by the parity progression ratio. The Ryder method overestimates the birth interval considerably if the parity progression ratio is small. The average birth intervals shown in Appendices B.5 and B.6 are obtained as the weighted sum of the intervals by completed parity, the weights being the probability that a woman in parity i will end up with j children (Chiang & Van Den Berg 1982; Feichtinger 1987, p.97).

A final measure characterizing the fertility career is the probability that a child born by a given age of a woman is the first, second, third or higher-order child. Of all the children born to the 1940-44 cohort, 43 percent are first children, 31 percent second children, 12 percent third children, and 14 percent fourth or higher-order children. Of the children born to the 1950-54 cohort (by age 35 of the mother), 46 percent are first children, 33 percent second children, 11 percent third children, and 10 percent fourth or higher-order children. The analysis confirms the observation that fertility change in the Soviet Union is characterized by an increase in the proportion of women with children, but a decrease in the number of large families.

The fertility career of Soviet women is characterized by an early start, mainly associated with early marriage. Women with several children at any given age start, on average, earlier than women with one or two children. The model replicates the observed relation between age at first birth and level of completed fertility. The relation may not be represented fully by the model since no micro-data are used and heterogeneity between women is not accounted for. Most women have at least one child and two-thirds have two or more children. At age 40 of the mother, the first child is 16 years old on average. It is 18 when more children are present.

The study of the fertility career of women is incomplete without consideration of the means to control fertility. Most women rely on abortion to control their fertility. In the Soviet Union, about 6 million abortions are registered each year against 5 million births. Abortions are concentrated in the European republics, mainly Russia and Ukraine. These republics registered 5.2 million abortions against 3.3 million live births (State Committee for Statistics 1989a, p.413). Population experts believe that women who practice abortion, have two abortions for each live birth. That means six pregnancies in a lifetime, four of which are aborted. The abortions that occur in the Asian republics are concentrated in those republics which have a high proportion of European nationalities (Russians, Ukrainians, and Germans), such as Kazakhstan. Contraceptives are not popular in the Soviet Union. Statistical data on contraceptive use are lacking. In the Socio-Demographic Survey of 1985, no information was collected on contraceptive use. Contraception was not an issue to be discussed before perestroika. Information collected in some special studies may have been published in medical journals. Experts state that the general public and the medical doctors have prejudices against hormonal contraceptives, due to expected health hazards. Other contraceptives are either not generally available or their quality is perceived to be questionable. Information on the availability and use of contraceptives is not published.

4. Conclusion

Nearly all Soviet women marry and have children. They marry and have children at young ages. In some parts of the country, half the brides are pregnant when they marry. Early marriage is both a determinant and a consequence of early fertility. Soviet women differ greatly from women in Western Europe in their early start of the marital and fertility careers. One-third of the women marry before their 20th birthday. Fifteen percent have at least one child at age 20; at age 25, 65 percent have one or more children. The paper uses recently published data and life table analysis to describe the marital and fertility careers. The model underlying the career paths is a Markov model. Data limitations prevent the estimation of more complicated models. The parameters of the career processes, the occurrence-exposure rates of marital change and fertility are estimated from the data. Once estimated, they permit a reconstruction of entire biographies (given the model). The biographic indicators presented in this paper include probability measures and duration measures.

No attempt has been made to link marital and fertility careers. The marital career is estimated from period data, whereas cohort data were available to generate the fertility career. Changes in marriage patterns may greatly affect period data, which should therefore be interpreted with the greatest care. An integration of both careers into a single staging process would benefit the assessment of the impact of changes in age at marriage on fertility. In the Soviet Union, age at marriage is however not the dominant factor in fertility, except in Asian republics. The housing situation forces many young couples to live with their parents. Since unmarried cohabitation is not generally accepted, marriage is the norm. Inadequate knowledge on contraceptives, prejudices against use of hormonal contraceptives even among medical doctors (partly because of the side effects attributed to their perceived low quality), and the inaccessibility of modern contraceptives of acceptable quality result in high fertility at young ages, and abortion as the main means of birth control.

The analysis of marriage and fertility at the country level, as done in this paper, can only provide a first impression of the processes that determine observed patterns. Because of the ethnic composition, great regional differences exist. Marital and fertility change in the Soviet Union cannot be understood without the regional and/or nationality component.

This paper is illustrative of a methodology that can easily be applied to republics and regions, given the rich data that have recently become available.

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Parity-Progression Fertility Tables for the Nationalities of the USSR[1]

Leonid Darsky and Sergei Scherbov

Foreword

The USSR is a whole world in itself, with an unexampled richness of geography, culture, language and people. This shows itself in the demography, especially in respect of fertility. The range there is wide, though there are other instances with equal range--in Canada in the 1930s from bare replacement in English-speaking Ontario to an average of 8 children ever born in French-speaking Quebec.

Such ranges are of course transitional; what they mean is that a process inevitable for all has come earlier to one group than to another. The process has gone to its natural culmination in Canada; in the USSR it is still proceeding.

This working paper recogniz.es the 17 largest nationalities, that divide in a seemingly bimodal fashion into two groups, one with a mean number of births ranging from 1.8 to 2.6, the other mostly around 6.

The method used is in principle the best, being based on a partial life history of individual women, with full details of their childbearing experience. The data was gathered in a 1985 survey, in which women were asked to recollect back to 1970-75. It does not entirely escape from the difficulty with any retrospective survey relying on the respondent's memory in that the quality of reporting differs systematically between the more sophisticated populations, that have lower birth rates and the less sophisticated, whose birth rates are in the high loop of the bimodal distribution. When errors are uncorrelated with the subject of survey they do little harm, but that is unlikely to be true on birth recollections.

Nonetheless these are positively the best data to be had for now, and they should be greeted warmly by students of the Soviet society. For through their bearing on demographic variables they also bear on the evolution of the USSR in its present dramatic transformation.

Nathan Keyfitz
Leader Population Program

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Introduction

When a married female recognizes her right and responsibility to define the number of children in her family and the time of their births, and at the same time tries to fulfil these intentions in practice, the number of children already born becomes the dominant factor when analyzing fertility processes. Many demographic factors are taken into account when a woman decides to bear another child. The age of the marital partners may become a limiting factor. Both husband and wife may think that it is too late to have another child, because at the time of their retirement that child could still be dependent on them. This argument is now very important in the USSR, because it is common to provide support (also financial) until the child finishes his education and even later, especially in the families of white-collar workers and intellectuals.

Another factor taken into account is the age of the youngest child. This is important both from an educational point of view, and from the possibility of women not working outside of the home. In the USSR, one receives benefits from the government for two children. When planning the family, a woman considers the optimal age interval of her children. And certainly simply having a small child in the family gives unmeasurable psychological satisfaction to its parents.

But in the end, the major influencing factor on a woman deciding to have another child is the number of children already born.[2] This priority is also mentioned by W. Lutz in the introduction to his study based on World Fertility Survey (WFS) data, where he analyzed fertility by parity for 41 developing and 14 developed countries (Lutz 1989). Unfortunately he did not have data for the Soviet Union so this large and very heterogeneous country was absent from the study. But we hope that by analyzing the data available, we can partly fill the gap and perform a separate interest.

In the Soviet Union the analysis of fertility by parity is very important. The majority of the subgroups in the population have already made the transition towards a modem type of reproduction behavior (controlled fertility); the other groups are gradually moving towards this goal. Especially distinct differences could be found between the different nationalities located at various stages of demographic transition. Nationality has now become the most important indication of differential fertility.

Method and data

In the socio-demographic survey of 1985 which covered 5 % of the total population, among others were the questions about reproduction biography. Women were asked about the year of their marriage, total number of children, and birthdate of each child (month and year). From this survey we could determine the distribution of married women by parity and the intervals between births. Our study was based on the information about one cohort of married women that gave birth to children between 197G-1974. For each married woman who bore a child of a given parity in 197G-1974 and remained married by the time of the survey (1 January 1985), we obtained information about the date of the next births. Data for the whole of the USSR are given in Table 1. The same data were available for most of the nationalities with populations exceeding 1 million (Appendix A).

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[2] 0ften in demographic analysis in order to find a solution within the framework of a relatively simple scheme and under the peculiarities of available information, the notion "number of children that a woman has" is substituted by "the number of children ever born". Under relatively low levels of infant mortality, such a substitution would not lead to substantial inaccuracy in the conclusions.

Table 1. Fertility in the cohort of married women, who bore the previous child in 1970-74. All nationalities.

Parity n	Number of women of parity N(n)	Parity progression ratio *1000 a(n)	Mean interval between birth t(n)	Standard deviation STD(n)
0	366843	952	1.39	1.468
1	302166	741	4.49	2.872
2	238974	349	3.81	2.786
3	92404	476	3.14	2.143
4	50643	639	3.00	1.856
5	36518	630	2.87	1.717
6	24759	673	2.75	1.568
7	16976	667	2.68	1.457
8	10580	637	2.61	1.452
9	5939	599	2.60	1.507

In most cases the number of observations for parities higher than 6 were insufficient for comprehensive study, and thus the indicators for these parities were not estimated. But the data for the first 6 parities were certainly reliable for all selected nationalities with high fertility (Uzbeks, Kazakhs, Azerbaijanis, Kirghiz, Tajiks, Armenians, Turkmen). For the nationalities with low fertility, the indicators for parities 5 and 6 were unstable and the number of observations insufficient. Thus a summary group of nationalities with low fertility was created, where the stability of indicators for parities 5 and 6 was definite and the information on parity progression ratios of parities 5 and 6 from this group was used for building fertility tables for each nationality with low fertility (Russians, Ukrainians, Byelorussians, Georgians, Lithuanians, Moldavians, Latvians, Estonians, Tatars and Jews). Using data from the combined group of parities 5 and 6 did not influence the final results for the individual nationality, because the number of births of these parities was very small (relatively) for women of reported nationalities and fertility indicators for these parities were similar. At the next stage the parity-progression ratios for parities 5 and 6 for each table were smoothed.

For parities 7 and higher we rejected the idea of estimating the parity-progression ratios for each nationality or combined group. We assumed the hypothesis that a female who has seven and more births does not at all restrict the number of children and does not use any means of contraception. We assumed that the probability of births of parities 7 and higher does not depend on parity-specific fertility regulation, which means that the intention of women to have another child is independent of her previous childbearing history. We had no evidence to consider differences in natural fertility of different nationalities. After the increase of fertility in the 1950s and 1960s the nationalities of Middle Asia achieved a very high level of reproduction. This was partly due to an improved health status of females. In the 1970s and 1980s there was a relatively high mortality level in the USSR, and there existed a differentiation of mortality level by nationality. But this phenomena least affected the female population in the reproductive ages. Thus we assumed that the fertility level of those groups of the USSR population who do not control family size corresponds or is at least very close to some standard that is inherent in populations with a very high fertility level.

Taking this into consideration we created the standard of natural fertility in the following way. From the large number of cohorts who finished their reproduction behavior and were studied in the framework of the WFS, we took only those whose Total Fertility Rate (TFR) exceeded 7.5. We averaged the data and built one single distribution of married females according to the number of children ever born. The cumulate of this distribution was approximated by the Gomperz-Makeham curve. This curve was taken as a standard of uncontrolled fertility. This standard does not pretend to reflect the maximum fertility level and some populations could easily have higher fertility. But in the framework of our study, the chosen level of natural fertility is quite suitable.

Using this curve we built a basic fertility table (Table 2). The relations between the indicators in the table are very simple:

$$a_n = \frac{l_{n+1}}{l_n}; W_n = l_n - l_{n+1}; F_n = \frac{\sum_{k=n+1}^{\infty} l_k}{l_n} - n$$

Since L. Henry (1953) suggested this method for measuring fertility, the technic of building fertility tables by parity was well elaborated (Lutz 1989).

Table 2. Parity-progression table, taken as a standard of natural fertility.

Parity n	Parity progression ratio *1000 a(n)	Number of women reaching parity l(n)	Women remaining at parity (n) W(n)	TFR for parity (n) and above F(n)
0*	971	1000*	29	7.5
1	973	971	27	6.7
2	962	945	36	5.9
3	947	909	48	5.1
4	936	861	55	4.4
5	910	805	72	3.7
6	867	733	98	3.1
7	837	635	104	2.6
8	781	531	117	2.1
9	714	415	119	1.7
10	661	296	100	1.4
11	604	196	77	1.0
12	502	118	59	0.7
13	454	59	32	0.5
14	398	27	27	0.0

*Women entering first marriage.

Taking into account our hypothesis that births of parities 7 and higher correspond to natural fertility, we accepted for all nationalities indicators from the standard starting from parity 7. We built a parity-progression table for the total population, 17 selected nationalities and two groups of nationalities - with high and low fertility (see Appendix Table B). Strictly speaking, tables that were constructed in the way described above are not cohort tables, because their indicators are not related to a particular marital cohort. These tables were generated using data related to different cohorts who bore children of different parities but at the same time (1970-74). But again, strictly speaking, that was not a synthetic cohort because in respect to each parity, only specific cohorts were observed in time. We believe that this approach is the most fruitful, because the analyzed process is not as distant in time from the beginning of observation, as in pure cohort analysis. At the same time some fictitiousness of a synthetic cohort is reduced to a minimum.

Using such an approach, it was possible to subdivide the table population into two subpopulations: those who control family sire and those who follow the pattern of natural fertility. If we consider that all those who bore the 7th child come from a subpopulation that does not restrict family sire, and all those who control the family sire already realized their procreative intentions, then the share of population that controls fertility could be estimated by dividing the number of those who gave birth to 7 or more children 17 by the related value in the standard population: $l_7^{stand} = 635$.

For example, if in a parity-progression table 353 Kazakh women out of 1000 gave birth to 7 and more children, then we can assume that 556 women out of 1000 never controlled their fertility and all indicators for this group correspond to the standard; but 444 did control family sire and their indicators are absolutely different; the total indicators for Kazakhs are weighted characteristics of the two subgroups.

Such calculations were performed for all nationalities and similar fertility tables were produced (see Appendix B). Figure 1 gives a graphic representation of an l_n column for several of the selected nationalities.

Of course it is not necessary to interpret all births from those who control family size as planned and desired. The culture of birth regulation in most of the groups is low, but moral availability and social acceptability of abortions in most of the groups approaches the situation where undesirable children are not born.

Results

Figure 2 gives the estimates of the proportion of women who control family size for all selected nationalities. The nationalities are ordered by the total fertility rate F0 in

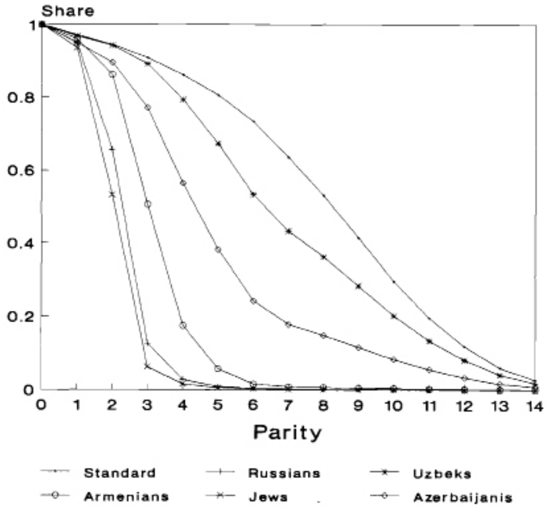

Figure 1. Share of women reaching parity

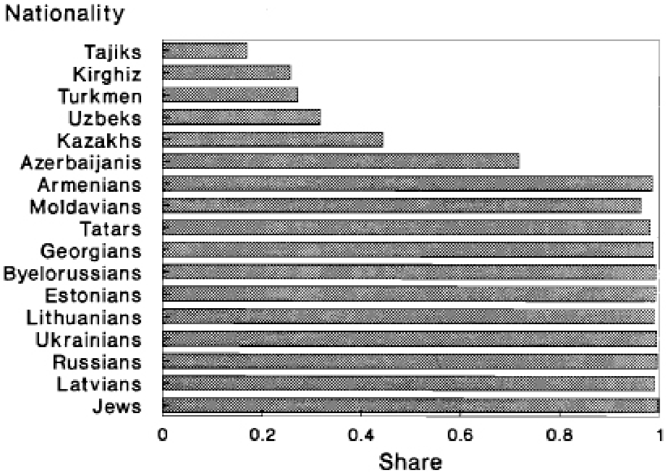

Figure 2. Share of women limiting family size

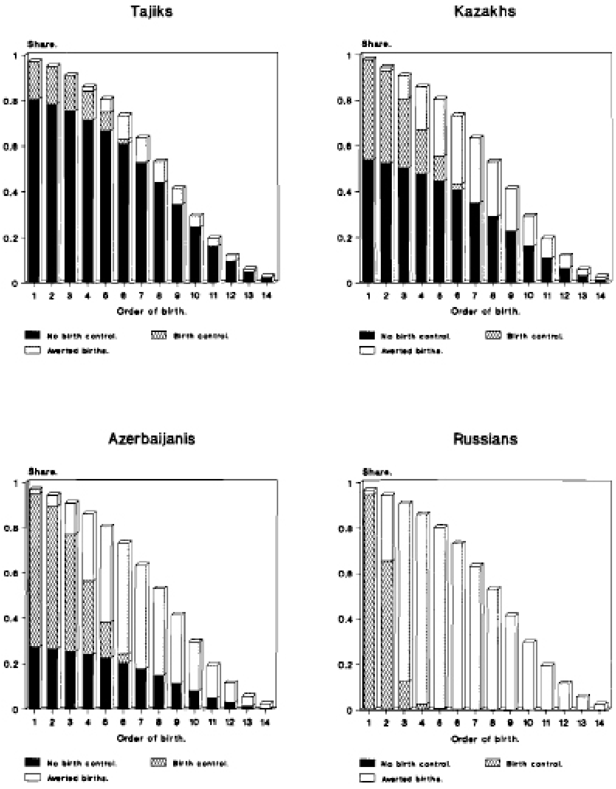

Figure 3. Share of children of each order born by different groups of women

descending order. As expected, the smallest share of women who control family size was obtained for the Tajiks (16.7%), slightly higher for the Kirghiz (25.7%) and the Turkmen (27.3%). The Kazakhs and Azerbaijanis are in the middle -44.4 % and 71.9% respectively. All other nationalities almost completely switched to a controlled type of reproduction, and the proportion of those who do not control family size is negligible from 3.6% for Moldavians to 0.2% for the Jews.

All of those who do not restrict the number of births have the same fertility level (according to our standard) with the mean number of children born by them at 7.5. But among those who control family size, the average number of children differs. In Table 3 we tried to present two indicators: the proportion of women who restricted the number of births and their TFR. Comparison of these indicators for different population groups demonstrates that they play a different role in the development of the fertility level.

The low fertility group consists of nationalities whose reproduction in most cases falls below replacement level. Among these, usually not more than 1% of the females follow the pattern of natural fertility, and they do not play an important role in the generation of total fertility level for these nationalities. Therefore the average number of children born in the whole group does not differ much from those who control family size. (This is not true only for Moldavians). In the group of nationalities with high fertility, that is true only for

Table 3. Share of women who limit family size and average number of children born to women of different nationalities.

Nationality	Share of women controlling birth per 1000	Mean number of births All women	 Birth controlling women
All nationalities	946	2.3	2.0
Low fertility group	995	1.8	1.8
Russians	996	1.8	1.8
Ukrainians	994	1.9	1.9
Byelorussians	993	2.0	1.9
Georgians	988	2.2	2.2
Lithuanians	991	1.9	1.9
Moldavians	964	2.6	2.4
Latvians	992	1.8	1.7
Estonians	993	1.9	1.9
Tatars	982	2.2	2.1
Jews	998	1.6	1.5
High fertility group	439	5.8	3.6
Uzbeks	317	6.4	3.9
Kazakhs	444	5.6	3.3
Azerbaijanis	719	4.4	3.3
Kirghiz	257	6.5	3.6
Tajiks	169	6.9	4.2
Armenians	987	2.6	2.5
Turkmen	273	6.5	3.7
Standard	0	7.5	-

Armenians, who traditionally were included into this group of high fertility. Together with the Moldavians in the 1970s-1980s, they occupied the intermediate position according to fertility level. But according to our estimate of the proportion of females who control family size, they have already moved to another group. Others nationalities are in a transition towards low fertility level.

It is also possible to distinguish between children born by those who control and those who do not control family size. An example of this distinction is given in Figure 3 for the groups with the most typical fertility behavior.

The results presented allow us to conclude that acceptance of the two-child family model delays from the practice of family size control. The distribution of females who restrict the number of births in this group of nationalities does not have a distinct mathematical mode. The number of children with which they stop the childbearing process is distributed more or less uniformly between three and five. At the same time for nationalities with low fertility, the mode for two children is explicit. Among Russians, Ukrainians, Byelorussians and Estonians, more than half of the females stop childbearing after having two children. Among these nationalities and also among Latvians, Lithuanians and Jews more than 70% of the marital couples stopped childbearing after having one or two children. The one-child family is in second place after the two-child family among these nationalities. For Georgians, Armenians, Moldavians and Tatars the mathematical mode is for two children. But in second position are the families with three children. Only among the Jews is the one-child family as popular as the family with two children.

The popularity of families with two children among nationalities with low fertility may also be confirmed by the data on the average number of children that a woman who gave birth to two children will bear in the future F_2. For low fertility nationalities this number is less than 0.5 (only for Moldavians about 0.8). Among the nationalities with high fertility but for subgroups who control family size, this indicator is higher than 1.5 except Armenians for whom it is only 0.8.

The diversity of the demographic situation in the USSR from a fertility point of view is amazing. If we compare the fertility level of the cohorts under consideration with the corresponding data from the WFS study, one can see that according to TFR, Tajiks are at the same level as Bangladesh, Columbia, Costa-Rica (6.9). Higher TFR was obtained only for Syria, Jordan, Mexico and Morocco. At the same time the level of TFR for Russians (1.8) was below almost all given cohort data except for the Netherlands.

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Demographic Aspects of Changes in the Soviet Pension System[1]

Sergei Scherbov, Nathan Keyfitz, Wolfgang Lutz, Christopher Prinz and Anne Wils

1. Introduction

Following the visit of a Soviet government delegation headed by Deputy Prime Minister N. Laverov, IIASA's Population Program was invited to provide statistical material on population dynamics in the Soviet Union that would be relevant for a restructuring of the pension system.

The material given in this paper provides some rough information on anticipated trends in the ratios between retired and working people as implied by the changing age structure of the population and alternative ages at retirement. This work is based on earlier research at IIASA that calculated various demographic scenarios for the republics of the Soviet Union up to the year 2050, assuming different future trends in fertility and mortality.

With respect to more specific questions of the currently existing and possibly changing Soviet pension system, the value of these data is very limited. Due to lack of knowledge of the details of the pension system, we can provide only a crude macro perspective. If a further, more detailed analysis is desired, a larger project on this topic could be launched by IIASA's Population Program.

2. Expected Future Changes in the Number of Workers per Pensioner in the Republics of the USSR

Generally speaking, the State revenues in the present Soviet pension system flow together into one fund, and State expenditures, for example pensions, are paid from this fund. This makes it difficult to determine how much of a worker's income or product is actually used to pay for pensions. In general, however, the working population is responsible for a country's income or product, and a portion of this income is used to pay for pensions. When there are more pensioners than workers, the burden of these pensioners on the workers increases. A rough estimation of this burden is the retirement ratio: the number of workers per retired person.

Real figures on the number of workers per retired person are difficult to obtain because some old people work part-time and some young people take a number of years off from work, etc. A fair estimation of the retirement ratio is to take the ratio of the number of people in the official working age (say 20 until le gal retirement age) to the number of people above the legal retirement age; in the USSR, retirement age is currently 55 years for women and 60 years for men. This assumes that men work an average of 40 years and women 35 years. As can be seen in Section 3, we found one estimation of the real average number of years worked by men and women in the USSR in 1985 to be 39 years for men and 31 years for women, and the mean actual age at retirement was estimated at 58.4 for men and 54.2 for women. This suggests that our calculation of the pension ratio in 1989 is

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a reasonable approximation for the USSR as a whole. However, it is not perfect, and there could be considerable deviations in some republics. We will return to this later.

To calculate the future pension ratio we first need a population projection. In earlier papers by this group (Scherbov & Lutz 1988) scenarios were made for the USSR population by republic up to the year 2050. A number of different assumptions were made about possible future developments of the population, each resulting in a different population pattern in the USSR. Here we use the results of the "convergence scenario" which assumes that fertility and mortality in all USSR republics converge at low fertility (a total fertility rate of 2.1, also called replacement fertility because the size of one generation will be exactly that of the previous) and high life expectancy (72 years for men and 78 years for women) by the year 2020.

Population projection is always prone to error, but for the next 20 years the population relevant to the pension system – the group of working people over 20 years and the group of pensioners – can be projected with near certainty. The reason is that all the people who will be at least 20 years old in the next twenty years have already been born, and mortality changes so slowly that we can be fairly certain as to what will happen to a group of people once they have been born. Fertility is more difficult to project, and the population projection becomes less certain further in the future.

Using this population projection, we can calculate the development of the pension ratio in the future using a time horizon to 2049. The pension ratio can change in two ways. First, the population age structure changes; e.g., as the population ages there are less people of working age per person in retirement age. Second, the legal age for retirement changes; e.g., if the age at retirement in the USSR increases from 60 to 65 for men, there will be more people working per pensioner. Figure 1 shows the development of the working age population and the pension age population from 1979, projected until 2049. The working

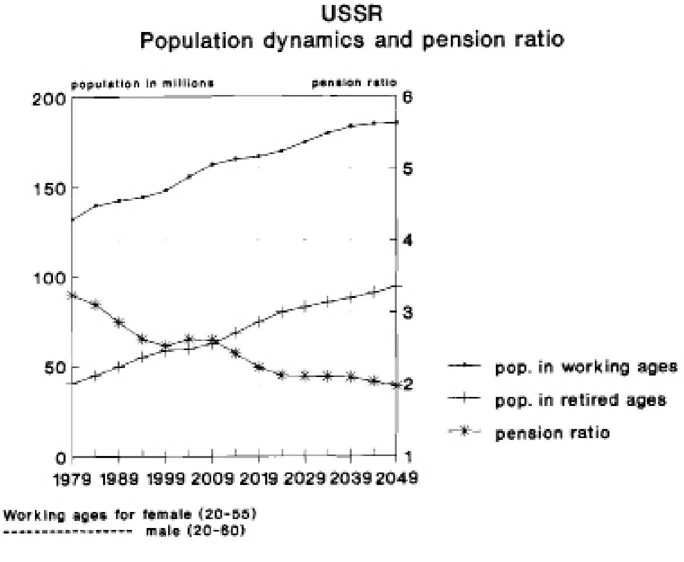


Figure 1. USSR population in working ages, population in pension ages, and pension ratio. Historical data from 1979--1989; projected from 1989--2049.

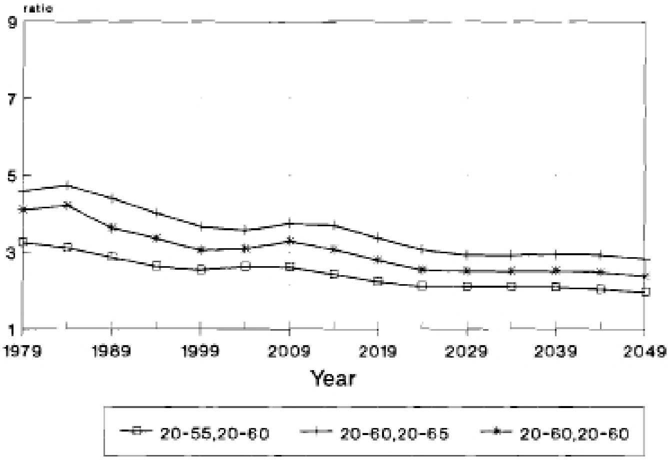


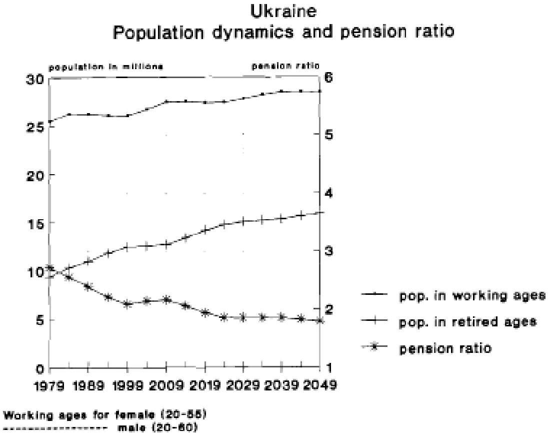
Figure 2. Changes in the USSR pension ratio according to three retirement ages, projected from 1989-2049.

population increases from about 132 million to 185 million in 2049. The population in pension age increases more quickly. The pension ratio is found by dividing the first population by the second. It was a little over 3.2 in 1979, and sank to a bit below 3 by 1989. In the future, this ratio will continue to decline to about 2. This means that the demographic situation in the Soviet Union for the pension system will get worse. *If everything stays the same – the pension system, the income tax, and average income – the State's costs for pensions would increase by 50% relative to income tax revenues*.

The second possibility for a pension ratio change is a shift in the pensionable age. Figure 2 shows the pension ratio from 1979--2049 using three different retirement ages. The lowest line with the square boxes shows the change in the pension ratio, as in Figure 1, using present retirement ages. The middle line, with the stars, shows the retirement ratio if women retire at 60. The ratio in 1989 is 3.65, about one-half person higher than the present retirement age. The ratio is about one-half person higher than the lowest line throughout the projection period. The top line, with the crosses, shows the retirement ratio if women retire at 60 and men at 65. In 1989, the retirement ratio would be about 4.4, again one-half per son higher than the line below it, and would decrease gradually to about 3. One idea that arises from observing this graph is that the 1989 pension ratio can be maintained in the USSR if the pension age is gradually raised by 5 years.

3. Distribution by Republics

The USSR republics are very diverse, and what looks one way for the USSR as a whole, may look quite different for individual republics. We were asked specifically to make some calculations by republic. The age-structures of the republics are very different, and the pension ratios are accordingly varied. Figure 3 shows the development of the populations in working ages and in retirement ages, and the retirement ratio in two extreme cases, Ukraine and Uzbekistan. In the Ukraine, the population in working ages in 1989 was about 26 million, in retirement ages 11 million, and the retirement ratio about 2.4. In Uzbekistan, the 1989 population in working ages was 8.3 million, in retirement 1.7 million and the pension



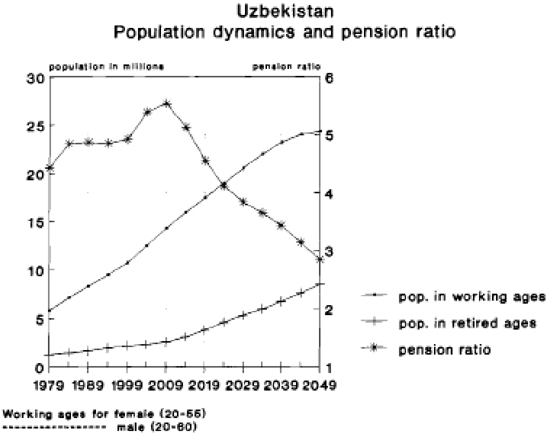


Figure 3. Population in working ages, population in pension ages, and pension ratio in the Ukraine and Uzbekistan. Historical data from 1979-1989; projections from 1989-2049.

ratio correspondingly high. In the next decades, the working age population of Uzbekistan increases very quickly, while the pension age population grows more slowly (reflecting slower population growth in the past). The retirement ratio in Uzbekistan increases until 2009. Then the population in pension ages begins to increase quickly and the pension ratio decreases to almost 3 in 2049. Ultimately, if we calculate further, it would stabilize at a level similar to the Ukraine if fertility and life expectancy in the USSR converge.

Figures 4 and 5 compare the pension ratios in the Ukraine and Uzbekistan using the three different retirement ages also seen in Figure 2 for the whole USSR. In 1989, the pension ratio in the Ukraine is much lower than in Uzbekistan. With the present retirement ages (bottom line), the pension ratio is about 2.4 in 1989 and decreases to 1.8. In Uzbekistan by contrast, the pension ratio is 4.9 in 1989. It increases for 20 years to 5.5, then decreases quickly to below 3 by 2049 (this is caused by our assumed drop in fertility and increasing life-expectancy which leads to an aging population and a lower retirement ratio).

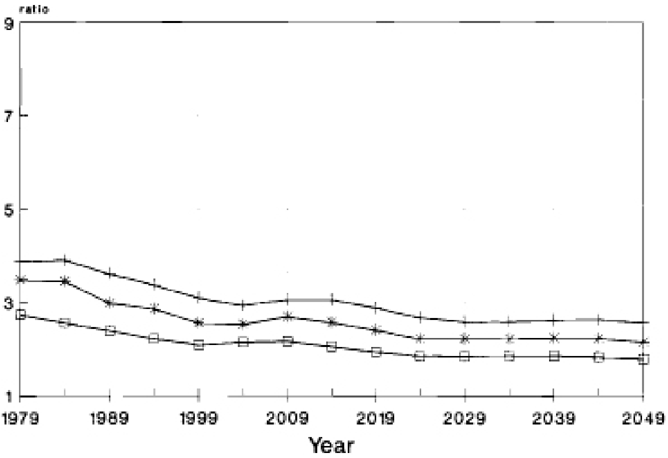


Figure 4. Changes in the Ukraine pension ratio according to three retirement ages, projected from 1989-2049.

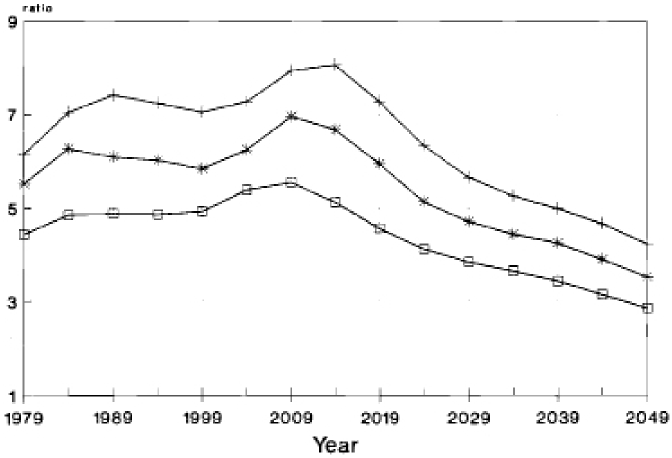


Figure 5. Changes in Uzbekistan pension ratio according to three retirement ages, projected from 1989-2049.

A gradual increase in retirement age by 5 years, such as that suggested for the USSR as a whole, would result in a slightly better pension ratio in 2019 in the Ukraine than in 1989. In Uzbekistan, the situation is completely different. Even without a change in the retirement age, the pension ratio improves for another 20 years. After that, aging proceeds so quickly that the retirement age will not be able to change quickly enough without causing disruption. *A sliding increase of the pension age might be advantageous in the Ukraine and other republics with a relatively old population, but the same increase would destabilize the pension system in Uzbekistan and republics with similar population dynamics* (Tajikistan, Turkmenia, and Kirghizia).

The figures for the other republics are in the Appendix. They suggest that the retirement ratio will decrease from 1989 onward in all republics except Uzbekistan, Turkmenia, Kirghizia, and Tajikistan. In these four republics, it will decrease quickly after 2015. This means that the demographic situation for the pension system will get worse for almost every republic, in some of them more quickly than others. H the Soviet Union wishes to improve the income of pensioners, it should consider that there will be relatively more pensioners to support. Either a greater chunk of the State budget would go to pensions, or the State could induce other ways to improve pensioners' income, such as promoting saving or investment in property, selling bonds, providing part-time jobs, etc. We will return to this in Section 5.

The figures also point out the extent of the variance between republics concerning the pension ratio. This is shown more clearly in Figure 6, comparing all republics in 1989 to 2019. The lowest ratios in 1989 are clearly in Russia, Ukraine, Byelorussia, Latvia and Estonia. Middle positions are found, for example, in Georgia and Moldavia. Very high pension ratios are found in all the Asian republics. These differences persist through time at least until the latest date shown, 2019. This suggests that *there is some reason to consider differentiating the pension system by republic*. The Appendix shows the same figures with a retirement age of 65 for men and 60 for women.

Should the Soviet Union decide to build a national pension system, we can make some approximations which republics would contribute more and which would consume more from the general pension fund. We calculate the proportion that each republic contributes to the total USSR working-age population. For ex ample, the Ukraine makes up 22% of the total USSR working-age population. We then calculate the proportion of each republic's

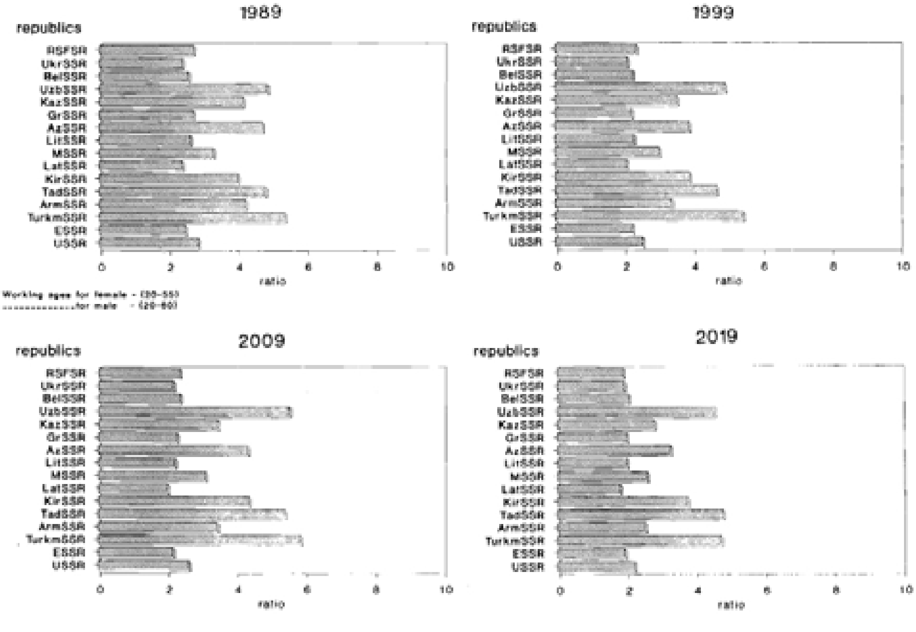


Figure 6. Pension ratios by republic in 1989, and projected in 1999, 2009, and 2019, according to present retirement ages (55 for women and 60 for men).

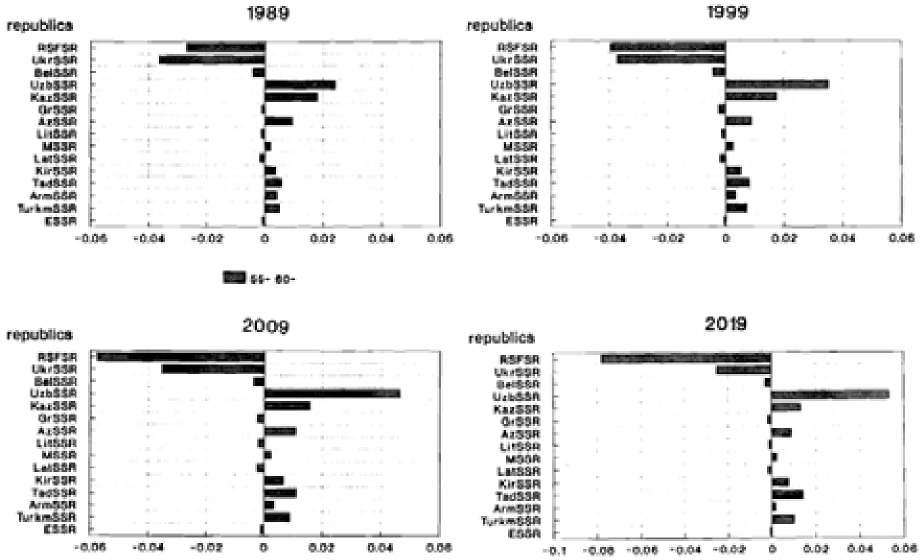


Figure 7. Net contributors and net consumers of State pensions, estimated by proportions in total population by republic. Left of zero: net consumers; right of zero: net contributors. With present retirement ages.

pension-age population to the total USSR pension-age population; for example in the Ukraine, it is 25%. If these two proportions are the same in a republic, this republic would contribute as much to the pension system as it consumes, if labor force participation and productivity were the same in all republics. If the working-age proportion is smaller than the retirement-age proportion (as in the Ukraine), the republic would be a net consumer and vice versa. The results of this calculation are shown for the present retirement age from 1989-2029 in Figure 7. Republics that have negative values, sticking out to the left of the zero line are net consumers. The countries with positive values, sticking out to the right of the zero line are net contributors. Many of the republics are close to zero, that is, they contribute about as much as they consume. The two big consuming republics would be Russia and the Ukraine, while the big contributors would be Uzbekistan and Kazakhstan. The net consumption of Russia increases until 2019, while the Ukraine becomes less of a net consumer. Uzbekistan increasingly becomes a net contributor until 2019, while Kazakhstan becomes a small net contributor the same size as Tajikistan.

These figures must be interpreted with care. For example, the figures say nothing about productivity. It is possible that a republic which would be a net consumer by age distribution would be a net contributor because of very high productivity of the working age population. Also, the picture shows results for whole republics, emphasizing the large republics. On a per capita basis, the picture would look different. The figures also say nothing about real retirement age, which could differ considerably from republic to republic. The Appendix shows the same figures with a retirement age of 60 for both men and women, and of 65 for men and 60 for women.

Table 1. Labor force participation rates in the USSR in 1950 and 1985 for men and women, three age groups, 55-59, 6D-64, and 65+.

	Males				Females			
Year	Total	55-59	60-64	65+	Total	55-59	60-64	65+
1950	57.4	89.5	86.5	49.0	48.1	50.9	42.6	35.0
1985	56.3	77.4	29.4	8.9	47.1	23.9	8.9	2.5

Table 2. Legal and estimated actual mean age at retirement for men and women in selected European countries and the USSR, 1950-1985.[a]

	Legal Retirement Age		Mean Age at Retirement			Differences Between Legal Age and Mean Age	
	Males	Females	Males	Females	Males-Females	Males	Females
Austria	65	60	59.8	58.9	0.9	5.2	1.1
Canada (est.)	65	65	63.1	63.4	--0.3	1.9	1.6
CSSR (est.)	60	55	59.3	56.4	2.9	0.7	-1.4
Finland	65	65	62.7	63.4	--0.7	2.3	1.6
France (est.)	60	60	61.6	61.6	0.0	-1.6	-1.6
FRG	65	65	60.5	61.6	-1.1	4.5	3.4
GDR (est.)	65	60	62.5	59.0	3.5	2.5	1.0
Hungary	60	55	59.6	56.0	3.6	0.4	-1.0
Italy (est.)	60	55	60.6	56.1	4.5	--0.6	-1.1
Netherlands (est.)	65	65	59.2	57.5	1.7	5.8	7.5
Poland	65	60	59.2	57.0	2.2	5.8	3.0
USSR 1985 (est.)	60	55	58.4	54.2	4.2	1.6	0.8
USSR 1970 (est.)	60	55	58.6	54.5	4.1	1.4	0.5
USSR 1960 (est.)			60.8	59.0	1.8		
USSR 1950 (est.)			62.7	61.1	1.6		
unweighted average	62.9	60.0	60.5	58.8	1.8	2.4	1.2

[a] Old-age and disability pen11ion11 (claimants for disability pen11ion11 aged 50 and over)

4. Interpretation: Some Reasons for Caution and More Information Needed

There were no figures available to us for the average retirement age by republic, but there are some indications for the USSR as a whole. The calculations above consider only legal retirement age, whereas in reality the people in the working force gradually retire. Table 1 shows labor force participation of three age groups around the legal retirement age, 55-59, 60-64, and 65+, for males and females in 1950 and 1985. There was a remarkable decline in labor force participation during these 35 years for both sexes, similar to the development in all European countries.

In 1985, for men five years before legal retirement, 23% are already out of the work force, while in the five years after legal retirement, 30% are still working. In the oldest age group, a small but not inconsequential minority of 9% are still working. For women the situation is similar, shifted five years younger.

In Table 2, the gradual retirement is reflected in the average age at retirement for European countries in 1985, and the USSR from 1950 to 1985. The average age at retirement departs from the legal age in almost all countries with a pension system, sometimes by as much as six years – in Poland and the Netherlands, legal retirement age is 65 for men, but the average age at retirement is 59.2. In those countries with a five year retirement age differential for men and women, the actual differences between male and female average retirement is less than these five years. In short, the legal age for retirement may serve as a guideline for retirement age but, depending how many loopholes exist, reality may depart more or less from it.

In the USSR, in 1950 the average age at retirement decreased from 62.7 for men and 61.1 for women to 58.6 and 54.5 respectively in 1970, and remained virtually stable until 1985, declining only minimally. It is evident from Table 2 that the USSR is the country with the lowest mean age at retirement of all the Europe- an countries shown!

Not only the average retirement age affects the real pension ratio, but also labor force participation. In our calculations for the pension ratio above, we implicitly assumed that everyone retires at the legal age and that everyone starts work at age 20. That implies men work 40 years and women 35. In fact, labor force participation in the USSR is not 100%, and the average number of years worked is shorter. As of 1950, the labor force participation trend decreases for men and women. We held present labor force participation constant from 1985-2020, and calculated how many years an average man or woman would work.

We also calculated the average number of years that would be worked if retirement age increased by 5 years in 1995, and the average retirement age became equal to this new legal retirement age. The results are shown in Table 3.

With the present mean age at retirement, the average number of years worked for men would decline from 39.16 in 1985 to only 37.68 in 2020 if labor force participation would remain constant at the 1985 level. For women, it would increase from 30.17 to 33.98 if labor force participation remains constant.

If mean age at retirement suddenly increases in 1995 to 65 for men and 60 for women, we would expect that the mean number of years worked would increase by the difference between the old average age at retirement and the new one, that is 6.6 (65 min us 58.4) years for men and 5.8 (60 minus 54.2) years for women. In fact, the average number of years worked increases much less – in our calculations it increases by 4.44 years for men and 2.72 years for women in 2000 – because the labor force participation in these age groups is not very high.

These two facts, the discrepancy between legal and average age at retirement, and the less than complete labor force participation suggest that if the legal age at retirement would be raised by five years in the USSR, the effect might not be as great as expected.

Table 3. Average number of years worked (AWY) by sex, 1985-2020 (2050).

Version a:	Legal age at retirement: 55 (females) and 60 (males) Mean age at retirement: 54.2 (females) and 58.4 (males)					
		1985	1990	2000	2010	2020	2050
Males	total	39.16	39.17	38.94	38.31	37.68	37.17
Females	total	30.17	31.26	33.14	33.96	33.98	33.61
Version b:	Legal age at retirement: 60 (females) and 65 (males) Mean age at retirement = legal age at retirement						
Males	total	39.16	39.17	43.38	43.73	43.57	43.09
Females	total	31.82	32.75	35.86	37.93	38.88	38.64

They also suggest that there might be some real differences between the pension ratios, as we calculated them above, and the actual situation in each Soviet republic. This is especially important if we are to find and analyze the differentials and inequalities between the republics. For instance, it could well be that the mean age at retirement in the more industrialized republics is lower than in the other republics, and that the industrialized republics are at the same time those which have a high proportion of elderly from the start. H this is true, it would accentuate the variation in the pension ratios of the Soviet republics even more than we observed above.

To find out more about this variation between republics, we need data on labor force participation rates by republic and sex to calculate the average number of years worked by a man or woman before retiring, and to estimate the mean age at retirement. The data for the new retirees per republic, sex and single year age group would make the calculation of the mean age at retirement more precise and could improve the calculation of the pension ratios.

As mentioned above, the pension ratios alone are not enough – there is differential productivity in the Soviet republics which might mitigate or even re verse some of the pension ratio differences observed above. The per capita productivity in each republic would help us to make a more precise picture of the demographic influence on the pension system in the republics of the USSR.

5. Some General Thoughts on Alternative Pension Systems: Combining State Pensions with Private Savings, Family Support and Continued Work Options

Like many of the other changes needed in the Soviet economy, the transition to a new pension system means at the same time hardship, and is also an opportunity to start anew on sound principles. This means a chance to avoid the mistakes of the past that are now recognized both in the East and West.

The state pensions in Western Europe and the United States which tax the present workers to pay those who are presently in retirement, originated at a time when many young people supported few old people. It was of rather low cost to the working people to fully support the old people via a state pension. Presently (and in the future) there are far less working people to support an enormously increased population of old people. The pension burden (number of working people per old person) has increased to such an extent that soon, if all people retire around age 60, there will not be enough workers to support them at tolerable tax rates if the pensioners do not have other sources of income – saved income in the form of bank accounts or life insurance, family community.

One mistake that has been made by many western countries is the notion that state pensions could be the sole support of old people. H state pensions cannot carry the whole burden of retirement costs, we suggest that the support system for old people should be a four legged stool:

1. State pensions;
2. Private savings;
3. Family and local community help independent of the state;

4. Protected sectors of the economy in which old people can work inefficiently, but yet making some contribution, and earning some (small) wage – for example, small scale farming, small retail stores, small scale service such as repairs.

The idea behind such a four-tiered system is that one should minimize state pension costs to relieve the working population of the burden of paying the pensions by encouraging the pensioners and the workers to use other ways of increasing retirement income.

5.1. State pensions

State pensions have developed in industrialized western countries since the beginning of the century, many of them maturing in the 1950s or 1960s. There is a wide range of pension systems in use, including a flat rate minimum pension for all, income dependent pensions, a combination of these two, a pay-as-you-go sys tem, and partial investment of workers' pension contributions.

In general, pensions have become more generous and retirement an accepted state. As a result, there are many cases where the old are perfectly fit and productive in the occupation they have been following, and they just want to retire sooner than nature dictates. The age of retirement is declining rapidly for male workers, and this presents a problem to the economy, especially at a time when the number of births and hence of young recruits is low. We believe that part of the cause is the wrong impression that politicians have given of the capacity of the system to maintain the old without having to work. In all countries, we need to get more information on the realities out to the public.

The high state pensions also may be correlated with lower savings rates and remove the necessity of having children to care for a parent in old age. We suggest that in general, the state pension should be enough to keep people alive, but not enough to discourage saving or make children unnecessary. Beyond that, a few further options could be considered.

From the above, it is clear that higher retirement ages considerably reduce the pension burden. Thus we suggest that pensions be sharply graduated upwards according to age at retirement. The basic principle ought to be that pensions are so low at low retirement ages that healthy individuals will prefer to keep on working. It might be that at current prices, those who wish to retire at age 60 be given the current 100 Roubles per month; those who retire at age 65, 150 Roubles; those at age 70, 200 Roubles. Of course, these are only suggestions; perhaps the numbers should be doubled given the current inflation.

A second possibility along these lines is to allow people to receive a portion of their pension even if they continue working. In the present system, when a person retires the State loses income (previous contributions of the retiree) while expenditures increase. H people are allowed to receive part of their pension while they continue working, this could induce such large numbers of them to keep working that the net effect would save the State money.

It should be recognized that some people will prefer to retire early and live very modestly; others will prefer to keep working so that they can live well when they retire. Some people will want to save a large part of their incomes while they are of working age, while others will want to save little but work to an old age. Giving people choices will help satisfy them, and this is all the more necessary when there are some difficult times ahead.

We also propose the choice of taking some years of pension at younger ages and working longer later. This takes advantage of the fact that people live longer and are in better health than ever in their 60s and 70s, and also boosts the pension tax paying morale of the workers because they can enjoy some of the fruits of their payments immediately. The “early pension years” could be used to re-train people for a new occupation in this time of rapid technical change, or to give ex tended maternity leave or extended educational leave. This would be compensated by working longer when others reach the regular age of retirement.

Another aspect of making the payments of pension taxes more agreeable to the workers is to separate this tax from other taxes. In many countries the state pension finances are separate from other state institutions. This has the advantage that people know they are getting something concrete in return for their contributions.

Much research already exists on different systems of state pension. If desired, an IIASA study could go deeper into the subject and make more concrete proposals based on the present Soviet pension system. The aim would be to introduce as little variation from the present as possible; sudden changes disturb people, and one should make the reform as consistent with their expectations as possible. The ideal is to remove the objectionable features of the present arrangement but leave in place those features that are good or harmless.

5.2. Private savings

State pensions can be the basic income in retirement. Private savings can supplement it. Every economy requires savings in order that it may invest, and the problem is how to encourage this. One of the most obvious ways is stimulating people to save for their old age. This saving can be private or collective in the form of private or public pension plans which invest the collective savings of all contributors. In the pa.st, it has been mostly private savings. In many countries, pension insurances are gaining popularity, and in Japan, the state pension scheme is so organized that a large fraction of the money paid by the workers is saved and invested, to be paid out later, along the principles of private saving.

High state pensions make individual saving unnecessary for individuals, despite their necessity for the community. But an even bigger element discouraging saving is inflation, especially when markets in industrial equities, real estate, etc., are inadequate. Far and away the biggest financial asset of the average American family is the ownership of the house or apartment they live in; the sale of that asset can help an old person a good deal in his or her later years. This could be an increasingly important means of saving in the USSR, especially since apartments are also up for sale.

Sooner or later the present inflation will be brought under control, but in the meantime some device is required so that savers will not be punished by inflation. One device is indexed government bonds. People would buy bonds, i.e., lend their 1990 Roubles with the assurance that they would get back on demand the equivalent in 1995 or 2025 Roubles. At present rates of inflation, this would mean that if they cash in their bonds 10 years later they would get more than twice as many of the Roubles then in circulation. The ratio would be worked out in a price index weighted according to the commodities used by old people of modest incomes.

It will be asked whether the State can afford to offer such bonds for sale. The answer depends on one thing only: the efficiency of the investment and production processes, e.g., the bonds can be used as mortgage on plants and productive operations or against the national economy as a whole.

The question as to what interest rate should be added for indexed bonds is not easy. One answer is no interest at all; we believe that people would buy them if they saw them as a safe repository of value, even if the real value would not in crease. But if the investment will produce goods that sell well at then current prices, bringing profits of 5% or 10% on the capital invested, then 1% or even 3% real return to bondholders may well be afforded. It will be necessary to be fairly concrete about the guarantee of repayment, given the known suspiciousness of the public regarding the government – common to all countries.

5.3. Family and local community help

One has to be careful about relying too much on families to assist parents in their old age since the same phenomenon that makes difficulties for state pension – low birth rates – also creates difficulties in individual families. Small families mean few children to look after parents. Moreover, in all countries – if the USSR is not included in these, it soon will be – the children seem to have lost the discipline they had in former times; they want to pursue their own careers and their own pleasures; just as having children of their own is a handicap to these, so also is having dependent parents. Indeed part of what has motivated state pensions is undoubtedly the disinclination of children to be financially responsible for their parents.

Yet children can be an important source of decreasing the social costs of aging. Children or the community can take over part of the care of aging parents so that these do not need to go to old-age homes, or to expensive hospitals, for example, by caring for them during a temporary illness, doing grocery shopping, or heavy housework, etc.

How can children be encouraged to take responsibility for their aged parents, for instance to have them living in the same or nearby premises? We need to investigate what privileges will entice children to help parents, perhaps allowing earlier retirement for a child who has a parent living in his premises. If the size of existing dwellings makes this impracticable, then nearby residence could be encouraged instead.

A part of the task of the Soviet authorities will be to make clear that no feasible state social security scheme will do the whole job of ensuring a good living for the old people. This also includes non-monetary aspects for which family support is of particular importance.

5.4. Work for the old in protected areas of the economy

At one time it was the old who were the repository of the community's productive knowledge; that is no longer true in most branches of activity. Technology is changing too fast in most lines of production. But the capacity of the old to learn new technologies is much greater than was believed in former times, when there was no need for such learning. We believe that re-training programs are required in many activities, and at a wide range of ages from 40 to 75. If people can be motivated to learn, they will prove unexpectedly adaptable.

Yet for those old who cannot be so motivated, or who suffer from physical or mental limitations, a host of occupations can be found that they can perform perfectly satisfactorily. Everything from night watchman on building sites to raising and selling vegetables, to certain kinds of inspection of manufactured products, could well take advantage of the diligence and reliability of many old people.

6. Conclusions

In sum, the broad concept of social security that we espouse depends on all four of the means by which old people can be supported, and not state pensions alone. People should be given the option of retiring at various ages, but the retirement at ages as young as 60 should be discouraged by low pensions for these, and much higher pensions for those willing to work longer, although certainly a prerequisite for this is the availability of enough jobs. Private saving should be encouraged, if necessary by indexed bonds, though this is a part of the solution only in the long term. Children looking after an aged parent should be offered some retirement for themselves. Those who are able to work should be encouraged to do so, either following an introduction to new technology or doing simple work. One could investigate the consequences of these various systems in the Soviet Republics.

Future Regional Population Patterns in the Soviet Union: Scenarios to the Year 2050[1]

Sergei Scherbov and Wolfgang Lutz

1. Introduction

In most countries of the world people call the Soviet Union Russia and its inhabitants Russians. This historically grown usage of the word Russian has long been incorrect but in the future it will even further lose its justification since soon less than half of the population of the Soviet Union will be living in the Russian Republic. When speaking about ethnicity this is even less the case because the Russian Republic also includes different ethnic groups.

In this study we will not look at ethnicity but only at regional differentials as given by the structure of republics. Part of the reason for this lies in the availability of data on vital statistics which are readily available only for republics. But in a very crude sense relative changes in the population composition by republics also correspond to changes in the composition according to major ethnicities.

The results of this study will impressively demonstrate the great regional variability of demographic patterns in the Soviet Union. As concerns fertility the Soviet Union includes populations with sub-replacement fertility as low as in many highly industrialized countries and regions (such as Tadzhikistan) with fertility levels higher than in most developed countries. Hence attempts to treat the Soviet Union as an homogeneous aggregate and prepare population projections on this highly aggregate level[2] have about the same value and justification as projecting the world population without differentiating by country or even continent.

This paper on the impact of regional demographic trends in the Soviet Union has two parts. First we study the trends in regional age-specific fertility rates since 1959 and assess by quantitative means the extent of family limitation and the current stage of the republic in the process of demographic transition. In a second part we define three different scenarios of future fertility and mortality trends for republics with the alternatives of continued diversity or convergence of fertility and mortality levels. Finally, the impact these alternative projections up to the year 2050 will have on the distribution of the Soviet population over republics and consequences such as differential pat terns of population aging will be discussed.

2. Recent demographic trends by republics

In 1987 the USSR population exceeded 281 million people (*Vestnik statistiki*, No. 5, 1987). The national average crude birth rate was 19.4 per thousand and crude death rate 10.6 per thousand in 1984-85, implying an annual natural increase of 8.8 per thousand. In 1983, 72.6% of the total Soviet population lived in the European USSR and 27.4% lived in the Asian parts.

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[1] Reprinted by permission from *IIASA*, Working Paper WP-88-104, pure.iiasa.ac.at/3102/. © 1988 IIASA.

[2] Recently Kingkade (1988) published scenarios for the population growth in the USSR to the year 2025 which does not give any regional breakdown.

Table 1. Proportions of the total population and of all births in the republics of the Soviet Union, 1970.

Republic	Population (in 'OOOs)	Proportion of USSR	Mean Age	Births		Difference in Proportion of Population and Births
				Absolute	Proportion	
RSFSR	130079.2	53.8	32.0	1900	45.0	-8.8
UkrSSR	47126.5	19.5	33.6	719	17.0	-2.5
BelSSR	9002.3	3.7	31.9	147	3.5	-0.2
UzbSSR	11799.4	4.9	24.6	402	9.5	4.6
KazSSR	13008.7	5.4	26.6	307	7.3	1.9
GrSSR	4686.4	1.9	30.9	90	2.1	0.2
AzSSR	5117.1	2.1	24.9	151	3.6	1.5
LitSSR	3128.2	1.3	32.9	56	1.3	0.0
MolSSR	3568.9	1.5	29.5	70	1.7	0.2
LatSSR	2364.1	1.0	35.8	34	0.8	-0.2
KirSSR	2932.8	1.2	25.9	90	2.1	0.9
TadSSR	2899.6	1.2	23.7	102	2.4	1.2
ArmSSR	2491.9	1.0	26.1	56	1.3	0.3
TurkmSSR	2158.9	0.9	24.1	77	1.8	0.9
EetSSR	1356.1	0.6	35.4	22	0.5	0.0
USSR	241720.1		31.2	4225		

More than half of the Soviet population lives currently in the Russian Republic but already less than half of all babies born in the Soviet Union are born in this large Republic that stretches from Leningrad to Vladiwostok. Certainly this will have implications on the future regional composition of the Soviet Union. Table 1 indicates the discrepancies between the share of the total living population and the share of all newborn. We see that in 1970 the Russian Republic, Ukraine, and Belorussian had significantly lower pro portions of all births than of the total population. All other republics have higher proportions of births (most significantly Uzbekistan) or approximately equal proportions.

In the 1970s birth rates declined in most of the high-fertility republics and in both urban and rural populations. Thus, in almost all the republics the rate of natural increase was lower in 1980 than in 1970. However, the differences between the growth rates in the highest and lowest-fertility republics increased even further to a factor of 22 between growth rates of 0.13% and 2.9% in 1980 in Latvia and Tadzhikistan, respectively.[3] Today, the Central Asian Republics, which contain one tenth of the total population, account for one third of the country's natural increase.

From this it becomes obvious that differential fertility will induce significant changes in the regional distribution of the Soviet Union. Hence, the results of the scenarios conducted in this study will heavily depend on the kind of fertility assumptions made. In order to evaluate the possible future paths of fertility in the republics of the Soviet Union a thorough study of fertility trends over the last decades is essential, especially when we believe that the process of demographic transition will continue and bring the fertility levels down substantially once it has started in a society. For this purpose we will focus in the following sections rather closely at recent trends in age specific fertility rates. From this we try to infer especially for the Asian republics at what point of the demographic transition they may be assumed to stand now, and what are likely paths for the future.

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[3] See: The USSR National Economy in 1980 (1980), Moscow, p. 32-33.

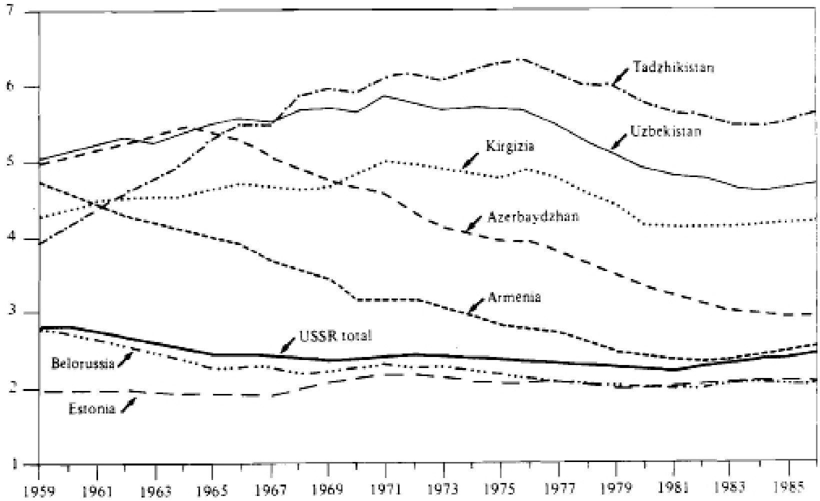

Figure 1. Total fertility rates in selected Soviet republics, 1959-1986.

Figure 1 depicts trends in the level of the total fertility rate between 1959 and 1985 for the complete Soviet Union and for eight selected republics. In spite of very divergent paths of development in the republics, the aggregate fertility levels in the complete Soviet Union look very stable around a TFR of 2.3 to 2.6. The only features worth noting are a slight decline between 1959 and 1965 and a very weak increase after 1982. This recent increase might be explained in part by a change in weights toward the high-fertility republics, but it might also reflect some real change in behavior, for example due to the measures accepted in the USSR in 1981 to increase fertility. In the Asian republics the TFR ranges between 4 and 6; while in the Baltic republics, the Ukraine, Belorussia and in the Russian Republic, fertility now is around replacement level or even somewhat below. These regional differences are explained by social, ethnic and other peculiarities of different segments of the USSR population.

Three Fertility Patterns

With respect to their trends over time, the Soviet republics might be classified into three categories: (1) the high natural fertility republics; (2) the middle, transitionalfertility republics; and (3) the low, controlled-fertility republics.

Uzbekistan, Azerbayazhan, Turkmenistan, and Tadzhikistan fall into the first category. Tadzhikistan, a relatively small republic bordering Afghanistan with currently the highest level of fertility (a TFR of 5.7 in 1986), shows clearly increasing fertility levels between 1959 and 1976, and only a slight decline thereafter. As in many high-fertility countries the reason for such a marked fertility increase lies most probably in a decreasing incidence of sterility and a shortening of birth intervals owing to changes in traditional behavior. The other three republics in this category show similar trends, with different turning points from increase to decline. In Azerbayazhan fertility increased until 1964 and then entered a steep and lasting decline. In Uzbekistan fertility levels peaked around 1970 and declined thereafter. Turkmenistan, which is not shown on the graph, followed a line of development almost identical to that in Uzbekistan, only at a slightly lower level of fertility.

The second group of republics includes Armenia, Kazakhstan, and Moldavia and shows steep fertility declines between 1959 and the late 1960s, followed by slower declines or even stability. These republics seem more advanced in their demographic transition than the republics in the first category, and we seem to have caught the tail of the fertility transition in the early 1960s. In Kazakhstan the pattern might be more complex be cause of the great heterogeneity of the population consisting of high fertility Kazakhs and other ethnic groups with low fertility (about 50% of the population).

The third, low-fertility category consists of republics that have already passed through the secular fertility decline and show only some post-transitional fluctuations. In Estonia (shown in Figure 1), which is one of the lowest-fertility republics in the Soviet Union, we note a relatively steep fertility increase between 1967 and 1971. We could speculate that this was a phenomenon similar to the baby boom in most Western countries. The pattern in Latvia is similar to that in Estonia. Lithuania followed the same trend at a somewhat higher level of fertility. The very populous Ukraine showed a slight decline at an already low fertility level until 1965 and almost no change thereafter – similar to the trend in the Russian Republic, which is by far the largest republic in terms of territory and people.

Applying the paradigm of demographic transition to the fertility patterns in the Soviet republics observed between 1959 and 1986 and discussed above, we may interpret the different categories of republics as representing different phases of a transition process from natural to controlled fertility, with Tadzhikistan and Uzbekistan the latest to follow this trend.

We investigate this point further by looking at age-specific fertility rates in selected republics and by calculating the index of family limitation.

Age-specific Fertility Rates

Data on fertility were taken from two sources (Vishnevsky et al. 1988; Urlanis & Borisov 1984). Figure 2 gives the trends in age-specific fertility rates for Estonia. The trends are generally rat her smooth. The greatest discontinuity was the almost 30% fertility increase for women in the prime childbearing group, age 20-25, between 1967 and 1972. After 1972 the rate remained stable at the new high level. Although we do not know the reason for this phenomenon, we may assume that it had to do with changes in marriages pattern because the fertility rate of women aged 15-20 also increased substantially; this increase, however, stretched out over a much longer period. In other groups the fertility increase was a short-term phenomenon visible also in the age groups 25-30 and 30-35. Beyond age 30 fertility declined slowly over the whole period. This is a clear indication of a controlled-fertility regime.

In Figure 3 we see the trends in age-specific fertility rates for Uzbekistan, a highfertility republic. The fertility of women between ages 20 and 30 increased from 1959 to 1976 and then slowly declined. For the next age group, 30-35, the increase lasted only until 1969. For women aged 35-40 the increase was less pronounced, but the decrease after 1970 was very strong. Women above age 40 show declining trends since the early 1960s.

What explains the fertility increase for younger women followed by a decline? We suggested above that the initial increase in already high-fertility republics was not due to an increase in desired family size, but due rat her to an increase in the biological potential for childbearing. We may assume that within a natural-fertility regime increases in average fertility levels can be explained by changes in the proximate fertility determinants: fecundability, breastfeeding and the exposure to intercourse. It seems safe to assume

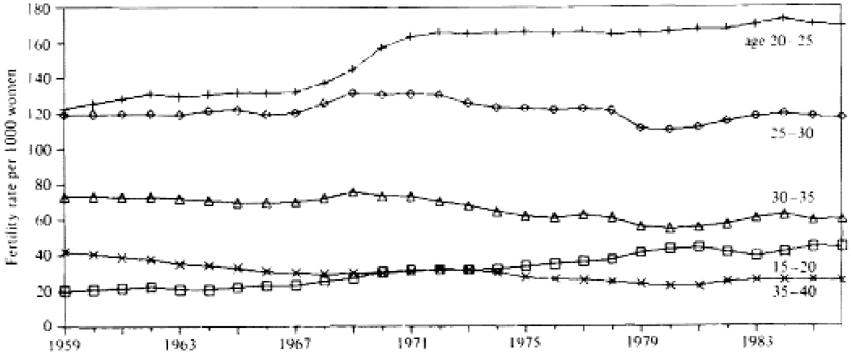

Figure 2. Age-specific fertility rates in Estonia, 1959-1985.

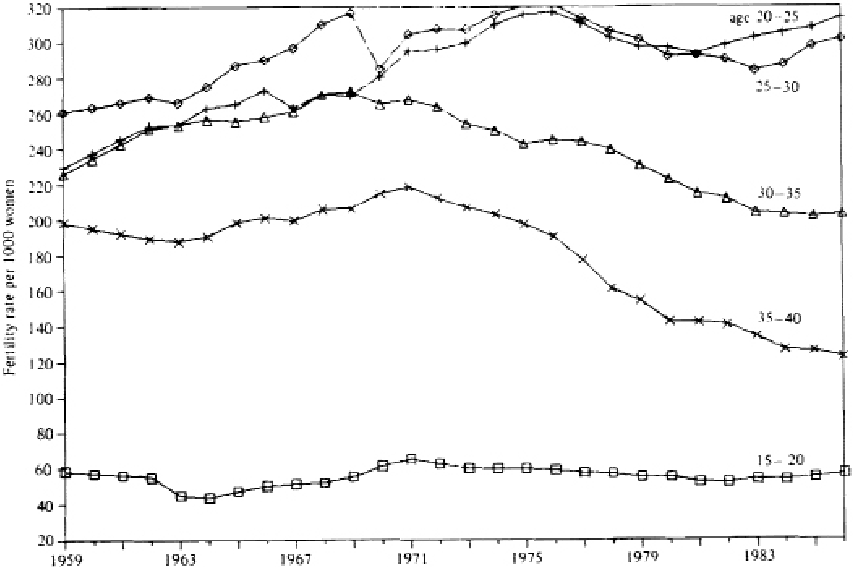

Figure 3. Age-specific fertility rates in Uzbekistan, 1959-1985.

that increasing educational standards together with improvements in health care in the high fertility republics resulted in lower sterility rates and higher monthly probabilities of conception. A reduction in the percentage of women breastfeeding, and in duration of breastfeeding, is another possible explanation for increased fertility levels. Fertility declines at higher ages, however, indicate the advent of fertility control, where women consciously limit family size when they already have the number of children they want.

Transition to Controlled Fertility

The change from natural to controlled fertility can best be illustrated by the change in the shape of age-specific fertility rates. If the curve is concave (to the origin) at higher ages, fertility is natural with older women still demonstrating relatively high fertility. If the curve is convex, this indicates controlled fertility because older women tend to have lower fertility in response to higher numbers of children. This is true regardless of the level of fertility.

Figure 4 gives age-specific fertility curves for Uzbekistan in 1959 and in 1985. In 1959 the curve was clearly concave. In 1985 the level of fertility was still high, but the shape had already changed dramatically and clearly indicated controlled fertility. It had about the same shape as the controlled-fertility curves in Estonia, Belorussia, and the average of the whole Soviet Union in 1985.

Coale and Trussell (1974) suggested a quantitative way to assess the degree of fertility control in a population. Among others, their model is designed to estimate a parameter m of fertility control, which measures the degree of deviation from natural fertility. We have applied the Coale-Trussell model to overall age-specific fertility rates from 1959 to 1986 (with the exception of a few years that were interpolated). This model was also used to convert empirical five-year age groups into one-year age groups. In almost all cases the fit was good. But for a few high-fertility republics we found that observed fertility rates in older age groups were higher than those estimated by the Coale-Trussell natural-fertility model. This might be a clue to the existence of a somewhat different standard natural-fertility schedule in Soviet Asia.

The degree of deviation from natural fertility measured by m is given in Figure 5 for three selected republics and the Soviet Union as a whole. Values of m close to 0 imply natural fertility. The shift to controlled fertility is gradual and takes place somewhere between m = 0.5 and m = 0.8. Thus, in Uzbekistan fertility proved to be virtually uncontrolled until the late 1970s. By 1985 Uzbekistan had reached a level of fertility control that is comparable to the highly advanced republics in the late 1960s. Although this index gives only a crude indication of a fertility regime, we clearly see the structural change for Uzbekistan and the

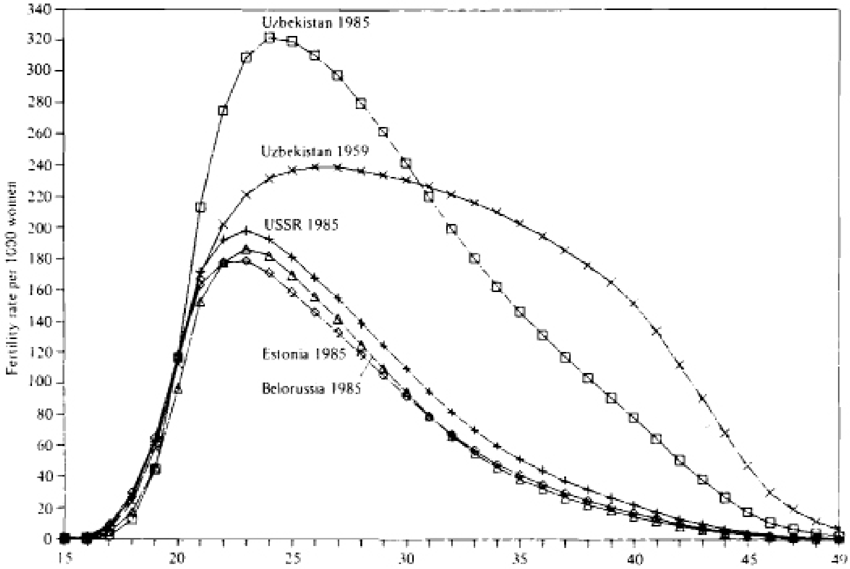

Figure 4. Age patterns of fertility in selected republics and years.

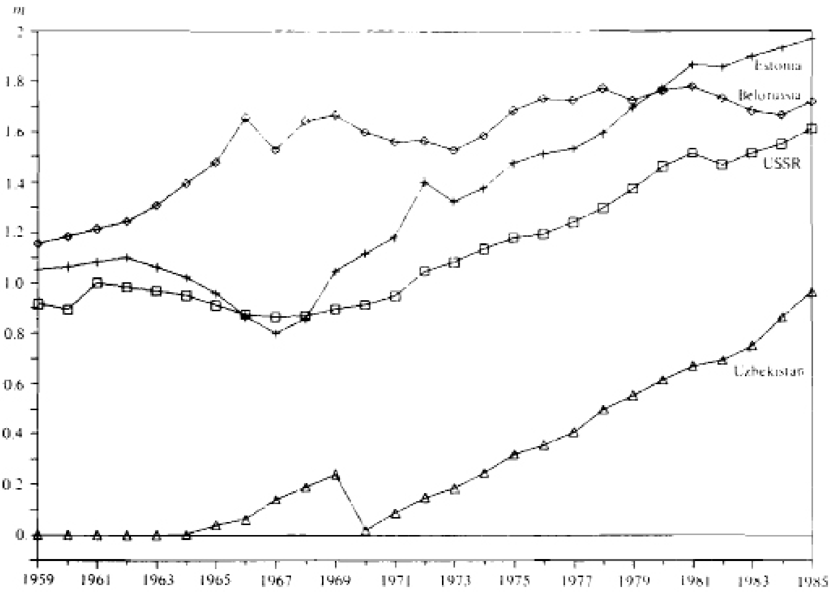

Figure 5. Index of family limitation m in selected republics, 1959-1985.

Table 2. Gross Reproduction Rates from 1970-1980 in the Soviet Republics.

Republic	1970	1975	1980
RSFSR	1.01	0.96	0.94
UkrSSR	1.04	0.97	0.98
Be!SSR	1.14	1.03	1.01
UzbSSR	2.83	2.62	2.45
KazSSR	1.66	1.56	1.46
GrSSR	1.28	1.17	1.12
AzSSR	2.06	1.82	1.66
LitSSR	1.14	1.05	1.00
MolSSR	1.31	1.19	1.19
LatSSR	0.99	0.93	0.94
KirSSR	2.44	2.27	2.06
TadSSR	3.03	2.99	2.88
ArmSSR	1.53	1.30	1.19
TurkmSSR	2.93	2.75	2.56
EstSSR	1.07	1.03	1.00

further trend toward higher control in the European republics and the Soviet Union as a whole.

Mortality

Mortality – the other important factor of population change – will be treated less extensively in this paper, partly because we do not believe that mortality variations will play an important role in determinating future differentials between the population size of

Table 3. Life expectancies at birth, 1970-1985 by republic.

Republic	1970	1980	1985
RSFSR	68.8	67.5	69.3
UkrSSR	70.9	69.7	70.5
BelSSR	72.4	71.1	71.4
UzbSSR	71.8	67.6	68.2
KazSSR	70.l	67.0	68.9
GrSSR	71.9	71.2	71.6
AzSSR	69.2	68.1	69.9
LitSSR	71.1	70.5	71.5
MolSSR	69.1	65.6	66.4
LatSSR	70.2	68.9	70.2
KirSSR	67.9	66.0	67.9
TadSSR	69.9	66.3	69.7
ArmSSR	72.9	72.8	73.3
TurkmSSR	68.4	64.6	64.8
EstSSR	70.4	69.4	70.4

republics and secondly because published data on mortality are more fragmentary than on fertility and hence do not allow the analysis of time series of age specific rates.

Table 3 indicates that in 1970 life expectancy was highest in Armenia (72.9) and Belorussia (72.4) and lowest in Turkmenistan (68.4) and the Russian Republic (68.8). Generally, it is amazing to see how low the mortality differentials are as compared to the fertility differentials described above. The difference between maximum and minimum is only 4.5 years or 6% of the Armenian life expectancy.

In 1980 published life expectancies are lower in each republic. Although the reasons for this partly significant increase in mortality in all republics over the 1970s remain unclear it seems to be the case that recently mortality conditions improved again. The figures published for 1985 show again significantly higher life expectancies than in 1980 and are in many cases higher than those reported for 1970. Again, Armenia is at the top of the list with a life expectancy of 73.3 years. The variation, however, seems to be higher in 1985 than it was in 1970.

For migration we will not make specific assumptions and only assume that the intensities remain as observed in 1970. For this reason there is also no need of discussion recent trends in migration here.

3. Setting scenarios for the future

The scenario approach to population projection does not attempt to produce one most probable variant or possibly other less probable variants which result from rather complex sets of assumptions that are mostly not explicit. In contrast to the usual variants the scenario approach makes explicit relatively simple alternative assumptions. The purpose of this exercise is to compare results coming from different sets of assumptions and assess the impact of alternative future trends. In a way this is closer to sensitivity analysis of assumptions in population projection than to the prediction of future population sizes.

Following this logic we also do not want to specify complex assumptions of changing patterns of age-specific fertility and mortality but instead define three very simple scenarios.

Rather than assuming future fertility and mortality trends for each republic separately we will define the scenarios according to two alternative principles concerning the differences between republics: convergence or continued diversity in fertility and mortality. Hence the following scenarios may be defined:

SCENARIO A: *Continued diversity*; fertility and mortality remain at the level observed in 1985

SCENARIO B: *Continued diversity in fertility*; convergence in mortality; fertility rates remain as in 1985, life expectancy increases gradually to 75.0 years in all republics by 2020, and remains constant thereafter.

SCENARIO C: *Convergence in fertility and mortality*; life expectancy increases gradually to 75.0 years and fertility goes to replacement level in all republics by the year 2020, both remain constant thereafter.

These three scenarios with the only alternatives of convergence and continued divergence seem to be much less specific than it could be made on the basis of the analysis of past fertility trends above. It was felt, however, that it would serve the comparative purpose better to give these rather general alternative scenarios, rat her than construct possible further trends in the continuation of the demographic transition based on the current status of the development in each republic. Even for some of the Asian republics where the progress in the fertility transition seems to be rather clear, the timing of the future fertility decline could have been only speculation. Even more so, in the very low fertility republics of Europe assumptions on the future course of fertility levels would have been pure guessing. The assumption of a population reaching replacement fertility at some point in the future is not very original and there is no substantive reason why the replacement level should be more probable than any other low fertility level. For our comparative analysis of future scenarios, however, such a simple assumption seems to serve its purpose as a point of reference for comparisons.

Comparison of results

The population projections were performed by using Dialog (Scherbov & Grechucha 1988) – the system that allows the analyst to quickly obtain and visualize the consequences of alternative assumptions about future developments in demographic processes.

Selected results of the three alternative population projections according to the scenario assumptions specified above will be presented below in tabular and graphical form. Table 4 shows the impact of the assumed alternative demographic trends in the republics on the total population size and mean age of the complete Soviet Union. Tables 5 to 7 give the changes in the relative size of the republic within the total Soviet population of the specified age groups for the three different scenarios. Figures 6a-c will indicate the changes in the proportions of newborn and Figures 7a-c trends in the mean age of the population for selected republics according to the three alternative projections. Figures 8 and 9 finally give 3-D views of the changing age structure over time of two major republics, Uzbekistan and the Russian Republic.

Table 4 shows that in terms of total population size and mean age the scenarios result in very different patterns by the middle of the next century. While the assumption of a continuation of current fertility and mortality levels (scenario A) will result in a population that is by far the youngest of the three scenarios, the projected population size will be between those of scenarios B and C. It is obvious that the assumption of continued present

Table 4. Resulting total population sizes (in millions) and mean ages for the total Soviet Union under scenarios A, B, and C.

	Scenario A		Scenario B		Scenario C	
Year	Total	Mean age	Total	Mean age	Total	Mean age
1970	242	31.2				
1975	253	32.3				
1980	264	33.1				
1985	275	33.6				
1990	285	34.2	285	34.2	285	34.2
1995	295	34.7	296	34.7	295	34.8
2000	304	35.1	306	35.3	304	35.5
2005	312	35.6	315	35.8	312	36.2
2010	320	35.8	325	36.3	320	37.3
2015	327	35.9	336	36.6	327	37.3
2020	335	36.0	346	36.8	333	37.9
2025	343	36.0	358	37.1	339	38.5
2030	351	36.0	369	37.1	344	38.5
2035	360	35.9	381	37.2	351	39.4
2040	369	35.7	392	37.1	351	39.6
2045	378	35.4	404	36.9	353	39.8
2050	389	35.1	418	36.6	354	39.9

Table 5. Shares of the individual republics on the total Soviet population and on certain age groups in the total Soviet Union according to Scenario A.

	Total			0-19 years			20-60 years			60+ years		
Republic	1980	2050	Dif.	1980	2050	Dif.	1980	2050	Dif.	1980	2050	Dif.
RSFSR	.530	.429	-.101	.472	.331	-.141	.554	.448	-.106	.558	.518	-.040
UkrSSR	.188	.145	-.044	.167	.115	-.051	.190	.149	-.040	.225	.172	-.053
BelSSR	.037	.030	-.007	.035	.024	-.011	.037	.030	-.007	.038	.035	-.003
UzbSSR	.055	.134	.080	.087	.207	.120	.043	.121	.078	.034	.069	.035
KazSSR	.057	.071	.013	.072	.078	.006	.055	.070	.015	.039	.062	.023
GrSSR	.019	.013	-.006	.020	.011	-.009	.018	.012	-.006	.019	.016	-.003
AzSSR	.023	.034	.011	.033	.041	.008	.020	.033	.013	.013	.026	.013
LitSSR	.013	.010	-.003	.012	.008	-.004	.033	.010	-.003	.014	.012	-.002
MolSSR	.015	.013	-.002	.016	.012	-.004	.015	.013	-.002	.013	.012	-.001
LatSSR	.009	.008	-.001	.008	.006	-.002	.010	.008	-.001	.012	.009	-.003
KirSSR	.013	.022	.009	.019	.030	.011	.011	.020	.009	.009	.015	.006
TadSSR	.014	.045	.031	.023	.075	.053	.011	.039	.028	.007	.019	.012
ArmSSR	.011	.013	.002	.014	.012	-.002	.011	.013	.002	.006	.015	.009
TurkmSSR	.010	.026	.016	.016	.041	.025	.008	.024	.016	.006	.012	.006
EstSSR	.006	.006	.001	.005	.005	.000	.006	.007	.001	.007	.007	-.000
USSR	1.000	1.000		1.000	1.000		1.000	1.000		1.000	1.000	

fertility levels together with an increase in life expectancy (scenario B) will result in a somewhat older population age structure (because the mortality improvement will mostly affect people above the mean age of the population) and because of lower death rates at constant fertility rates also in a larger population size. According to scenario B the Soviet population would increase by more than 70% between 1970 and 2050 to 418 million.

An assumed convergence of the fertility levels in all republics towards replacement by the year 2020 together with convergent and somewhat increasing life expectancies results in a rapid aging of the Soviet population. While the total population size would stabilize

Table 6. Shares of the individual republics on the total Soviet population and on certain age groups in the total Soviet Union according to Scenario B.

	Total			0-19 years			20-60 years			60+ years		
Republic	1980	2050	Dif.	1980	2050	Dif.	1980	2050	Dif.	1980	2050	Dif.
RSFSR	.530	.434	-.096	.472	.331	-.142	.554	.449	-.105	.558	.524	-.033
UkrSSR	.188	.144	-.045	.167	.114	-.053	.190	.148	-.042	.225	.169	-.056
BelSSR	.037	.029	-.008	.035	.024	-.011	.037	.030	-.007	.038	.034	-.005
UzbSSR	.055	.133	.079	.087	.209	.123	.043	.122	.079	.034	.068	.034
KazSSR	.057	.071	.013	.072	.078	.006	.055	.070	.016	.039	.062	.023
GrSSR	.019	.013	-.006	.020	.011	-.009	.018	.012	-.006	.019	.015	-.004
AsSSR	.023	.034	.011	.033	.041	.008	.020	.033	.013	.013	.026	.012
LitSSR	.013	.010	-.003	.012	.008	-.004	.013	.010	-.003	.014	.012	-.002
MolSSR	.015	.013	-.002	.016	.012	-.004	.015	.013	-.001	.013	.014	.001
LatSSR	.009	.008	-.001	.008	.006	-.002	.010	.008	-.001	.012	.009	-.003
KirSSR	.013	.022	.009	.019	.031	.011	.011	.021	.009	.009	.015	.006
TadSSR	.014	.044	.030	.023	.075	.053	.011	.039	.028	.007	.018	.011
ArmSSR	.011	.013	.002	.014	.012	-.002	.011	.013	.002	.006	.013	.007
TurkmSSR	.010	.027	.017	.016	.043	.027	.008	.025	.017	.006	.013	.008
EstSSR	.006	.006	.001	.005	.005	.000	.006	.007	.001	.007	.007	-.000

Table 7. Shares of the individual republics on the total Soviet population and on certain age groups in the total Soviet Union according to Scenario C.

	Total			0-19 years			20-60 years			60+ years		
Republic	1980	2050	Dif.	1980	2050	Dif.	1980	2050	Dif.	1980	2050	Dif.
RSFSR	.530	.515	-.015	.472	.511	.039	.554	.514	-.040	.558	.526	-.032
UkrSSR	.188	.172	-.016	.167	.174	.007	.190	.172	-.016	.225	.169	-.055
BelSSR	.037	.034	-.003	.035	.035	-.001	.037	.035	-.003	.038	.034	-.005
UzbSSR	.055	.071	.016	.087	.073	-.014	.043	.071	.027	.034	.067	.033
KazSSR	.057	.062	.005	.072	.062	-.010	.055	.061	.007	.039	.062	.023
GrSSR	.019	.014	-.005	.020	.013	-.006	.018	.013	-.005	.019	.015	-.004
AzSSR	.023	.026	.003	.033	.027	-.007	.020	.026	.006	.013	.025	.012
LitSSR	.013	.012	-.001	.012	.012	-.000	.013	.012	-.001	.014	.012	-.002
MolSSR	.015	.014	-.001	.016	.014	-.002	.015	.014	-.001	.013	.014	.001
LatSSR	.009	.010	.000	.008	.010	.002	.010	.010	.000	.012	.009	-.003
KirSSR	.013	.015	.001	.019	.015	-.005	.011	.014	.003	.009	.015	.006
TadSSR	.014	.020	.006	.023	.021	-.002	.011	.020	.009	.007	.018	.011
ArmSSR	.011	.013	.002	.014	.013	-.001	.011	.013	.002	.006	.013	.007
TurkmSSR	.010	.014	.004	.016	.014	-.002	.008	.014	.006	.0016	.013	.007
EstSSR	.006	.007	.002	.005	.007	.003	.006	.008	.002	.007	.007	-.000

around 350 million after 2035, the mean age of the population would increase very rapidly to about 40 years by the middle of the next century. This would mean an extremely high degree of aging even by the standards of currently rapidly aging societies in Western Europe.

From the figures and tables referring to the individual republics and comparing the changes in their relative sizes, it becomes apparent that the differences between scenario A and B are much less than their difference from scenario C. This indicates that the assumption made on fertility trends have greater impact on the future population composition than those made on life expectancy.

Assuming constant fertility and mortality rates (scenario A) will result in very dramatic changes in the population structure of the Soviet Union. The Russian Republic that currently has more than half of the Soviet population would increase in absolute terms from 140 Million to 183 Million by 2050 but in relative terms it would shrink by more than 10 percentage points to slightly above 40 percent of the total Soviet population. In sharp

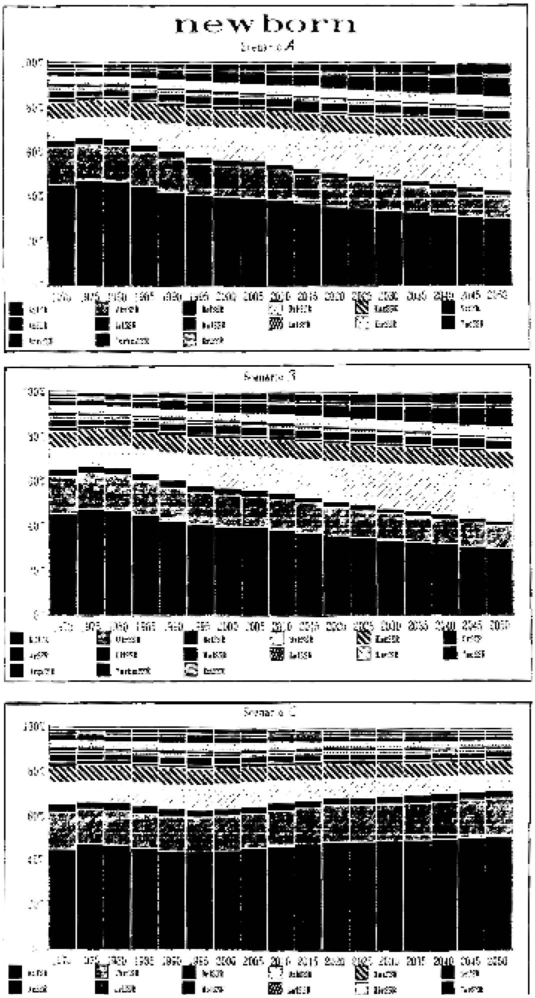

Figure 6. Proportions of all births in the USSR by republics 1970-2050 under the scenarios.

contrast to this Uzbekistan would almost double its population size and increase its share of the total Soviet population from 5% to 13%. Tadzhikistan and Turkmenistan will also grow at a similar speed under assumed constancy of present fertility and mortality rates. On the loosing side are aside from Russia, Ukrainia, Belorussia, and Georgia. The Baltic Republics would grow at about the same speed as the total Soviet Union and therefore hold their relative position.

For the young age group (0-19) these changes under assumed constancy of rates would be even more pronounced. In 2050 only 33% of the young people would live in Russia whereas more than 20% would live in Uzbekistan, and 8% in Kazakhstan and Tadzhikistan each. The same pattern is apparent in the graph of the relative distribution of newborns by republic (Figure 7a). For the older age groups the changes go into the same direction but are less pronounced than for the total or for the younger age groups. This is not only due to the fact that those people belong to the still smaller cohorts already born or to be born in

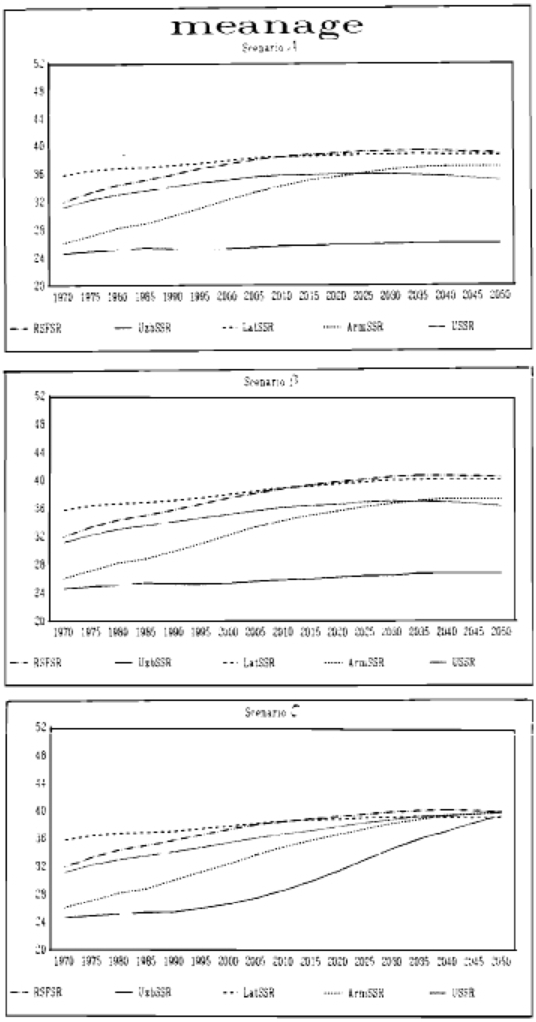

Figure 7. Trends in mean ages of the population 1970-2050 for the USSR and selected republics under the assumptions of scenarios A, B, and C.

the next years, but is also due to assumed persistence in mortality differentials that indicate somewhat lower life expectancies in the Asian parts

Another scenario that assumes constant fertility levels for each republic but an convergence in mortality towards a life expectancy of 75 in all republics (scenario B) results in essentially the same pattern as described above for scenario A. One difference between the results from the two scenarios is that the loss in the relative size of the European republics will be even higher for republics that already now have high life expectancies. The Russian Republic with currently relatively adverse mortality conditions would hence profit from the assumed increase in life expectancy more than e.g. Ukraine and Belorussia and would show a faster increase of its population than under scenario A. Because some mortality improvement is assumed in every republic, each of them will grow faster than

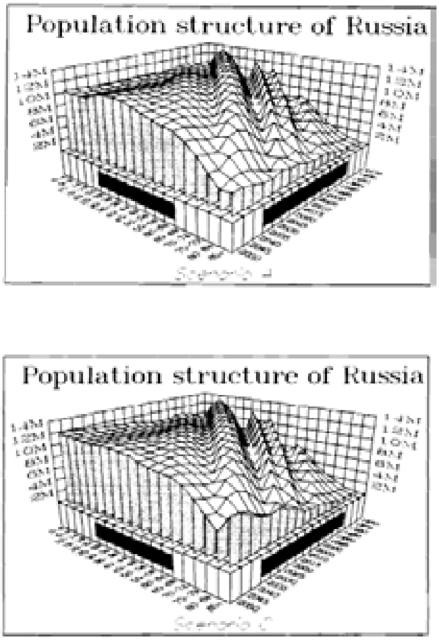

Figure 8. 3-D presentation of the population age structure m Russian Republic 1970-2050 as projected under scenarios A and C.

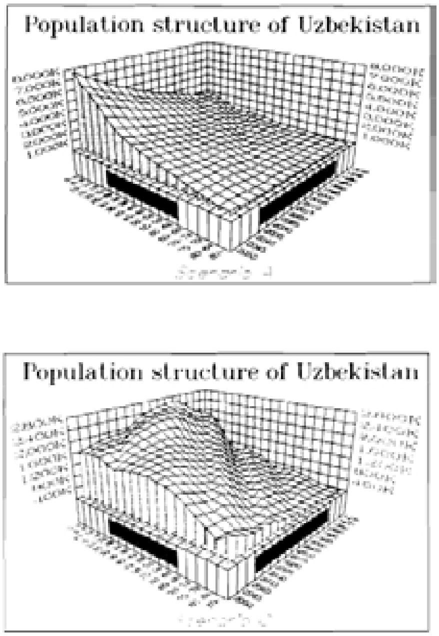

Figure 9. 3-D presentation of the population age structure in Uzbekistan 1970--2050 as projected under scenarios A and C.

under scenario A and the total population of the Soviet Union in 2050 would be 418 Mil lion instead of the 389 Million under scenario A, as discussed above.

The assumptions of convergence in mortality and fertility (scenario C), finally, will have a very great impact on the population structure. All republics would grow substantially, even those who have currently sub-replacement fertility such as Russia and the Ukraine. But for the currently high fertility republics the growth would be much less than under the previous two scenarios. As a consequence of the above stated trends a convergence in fertility towards replacement level in all republics would lead to much less significant changes in the share of individual republics in the total Soviet population.

Figures 8 and 9, finally, give 3-D presentations of possible changes of the age structure under the assumptions of scenarios A and C for two selected republics, Russia and Uzbekistan. Since in the Russian Republic fertility is already below replacement level, now the future trends will go towards a rectangularization of the age structure in both cases. Under scenario C the assumed increases in life expectancy result in a clearly greater number of people above age 60 under scenario A. Especially the cohorts of the Russian baby boom in the 1960s would profit greatly from the mortality improvement. Hence the ridge crossing the figures diagonally is much stronger towards the older end under scenario C than under C.

For Uzbekistan the difference between the two scenarios is much more dramatic. Under assumed constant fertility and mortality rates the population would explode and show the typical pattern of a very high fertility country. Under an assumed trend to wards replacement level by 2020, however, the largest cohorts would be born towards the end of the century followed by a steep decline in births. In the very left corner we can then even see the weak echo of these larger birth cohorts. If fertility should enter such a steep decline in Uzbekistan as it already did in Armenia and later on in Azerbayazhan, the future population structure would by the middle of the next century become similar to today's age structure in the European parts of the CSSR.

Concluding Remarks

All scenarios defined m this study indicate that the Soviet Union currently is experiencing a significant restructuring (*Perestroika*) also in demographic terms and that these trends will continue even stronger over the next decades. In case of a convergence of the fertility trends of all republics the change in the population structure would be less than in the case of a continuation of current diversity.

For demographers changes in the Asia republics can give a very interesting lesson on demographic transition that has not been studied much so far.

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Mortality in the Former Soviet Union. Past and Future[1]

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1. Introduction

The purpose of the study is to analyze recent trends and to project mortality by cause of death for the former USSR republics. The history of mortality in the former Soviet Union differs from the trends in other regions in several respects. Mortality history is generally studied within the context of the epidemiological transition. The first stage of this transition is the restriction of extraordinary periodical increases of mortality by such causes as particularly dangerous infections (cholera, smallpox, typhus and some others) and famine. The second stage is characterized by further extension and intensification of social control over exogenous factors of immediate impact; as a result mortality, caused by principal infections (first of all child infections, diarrhea, tuberculosis), respiratory diseases (influenza, pneumonia) and some others, decreases drastically or is even eliminated. The second stage manifests itself in the background and is the result of economic growth and industrialization. The mortality level at this stage is substantially influenced by such negative consequences of the industrial revolution as environmental pollution and stressors; as a result the quasi-endogenous mortality (caused by circulatory system diseases and malformations in younger ages as well as by accidents) increases. The third stage is the gradual elimination of negative industrialization consequences and quasi-endogenous mortality along with further eradication of purely exogenous components. These processes are based on measures for environmental protection, improvement of labor and domestic conditions, and promulgation of a healthy, rational mode of life. It increases mean death age by principal endogenous and quasi-endogenous causes of death. The elements of the fourth stage are only beginning to manifest themselves in the countries with minimal mortality levels. The major features of this stage are the further decrease of infant mortality due to preventive measures, efficient treatment of hereditary and congenital diseases, and mass nursing of prematurely born babies. At present the fourth stage can be considered a result of a highly efficient and developed health system.

The subject of the present study is recent mortality, i.e. mortality since 1980. Trends in male and female mortality are studied by cause of death for 12 former Soviet republics. The following groups of causes of death are considered: diseases of the circulatory system; neoplasms; accidents, poisonings and violence; diseases of the respiratory system; infectious and parasitic diseases; diseases of the digestive system and a group of all others and unknown causes. The former republics included in the study are: Armenia, Azerbaijan, Byelorussia, Georgia, Kazakhstan, Kirghizia, Moldavia, Russia, Tajikistan, Turkmenia, Ukraine, Uzbekistan. We did not include in our study the former Baltic republics because of the historical specifics of that region's demographic processes, and because all of the Baltic republics had already become independent states when we started the study. We hope that a simultaneous analysis of the 12 republics allows a better understanding of the recent mortality dynamics in the former USSR.

Trends in mortality dynamics in the republics of the former USSR may seem rather logical when compared to the world trends in mortality and the trends anticipated by the theory of demographic transition (Bourgeois-Pichat 1952; Bourgeois-Pichat 1978) in mortality. Thus

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despite the mortality increase from neoplasms, the level in many regions remains lower than in developed countries, and the mortality level from numerous chronic diseases that are included in the group “all others and unknown causes” is so low that it advocates for the poor level of differential diagnostics and unjustified transfer of deaths from rare chronic to deaths from diseases of the circulatory system (Andreev 1987; Andreev 1988; Andreev 1990). Mortality from infectious diseases, diseases of the digestive system and especially respiratory diseases in most of the regions consequently decreases in full agreement with the theory of demographic transition.

The epidemiological transition started later in the former USSR than in Western Europe (Andreev 1992). The first stage of the transition was over at the end of the 19th century, several decades later than in Western Europe. The second stage of transition was over in the mid-1960s in most of the USSR when life expectancy approached the level of the major Western countries. In this period, new negative tendencies emerged in the dynamics of USSR population mortality which was first apparent in the growth of mortality rates of males aged 15-59 and then spread over the female population and older ages (Dmitriyeva & Andreev 1987). The decline of life expectancy compared to 1966 was connected first of all to the increase of mortality of circulatory system diseases and accidents. Thus in 1980 life expectancy of males declined by 3.75 years (by 2.14 years due to circulatory system diseases, by 1.24 years due to accidents) compared to 1966. Life expectancy of females declined by 1.74 years, and the negative influence of mortality growth due to circulatory system diseases and accidents was 2.09 years, being partially compensated by mortality dynamics from other causes of death. A comparison of the data with the general pattern of demographic transition indicates that the dynamics of USSR mortality in the 1960s to early 1980s fully demonstrated the negative aspects that are typical for the second stage of the epidemiological transition.

From the prospect of the dynamics of mortality, the years 1980-1990 seem to look more optimistic than the preceding 15 years (1965-1979), when mortality from chronic diseases and accidents was rising steadily. But the period 1980-1990 is definitely not a homogeneous one.

Using statistical data (without adjustment for infant mortality and mortality in the older ages) we estimated for males and females the change in life expectancy relative to 1980 as a result of age-specific mortality changes of a certain age group due to a particular cause of death (see Figure 1 in Appendix A). The method of components was used for this analysis (Andreev 1982). We can observe that from 1980 until 1984, life expectancy increased slightly due to a decline in diseases of the respiratory system (both sexes), in part due to the age group 0-14, and in accidents (males). In 1984 mortality from diseases of the circulatory system contributed to the decrease in life expectancy compared with preceding years partially because of a severe influenza epidemic in the country; most of the negative effects were produced by the age group 60+.

A rapid increase in life expectancy followed after 1985. Between the beginning of 1985 and 1987, male life expectancy increased by 2.6 years and female life expectancy by 1.1 years due to a reduction in accident mortality. Month-by-month analysis of the dynamics of accident death rates proves that this decline in mortality is the immediate result of drastic measures taken in May 1985 against drunkenness in the USSR (Andreev 1992). The declining mortality from diseases of the circulatory system and respiratory diseases contributed to a further increase in life expectancy. The major negative contribution to life expectancy (though small) was from neoplasms and a group of causes called “other and unknown”. Starting in 1988 negative tendencies in life expectancy especially for males appeared again.

For males the decrease in life expectancy was attributed to an increase in mortality from accidents, poisoning and violence, almost entirely in the age group 15-59. For females new tendencies in this group were also negative, although not as pronounced. Diseases of the respiratory system continued to contribute towards an increase in life expectancy for both males and females. Special attention should be drawn to the group of other and unknown causes which includes mortality cases from numerous chronic diseases. Although the mortality from this group of causes is relatively low, the negative jump in life expectancy in 1990 resulted, from our point of view, from a lack of drugs and inadequate treatment especially of patients suffering from numerous chronic diseases.

Variations in mortality are attributed to two factors: contemporary and historical. Contemporary factors are usually referred to as ‘period effects’. In the absence of better data, they are approximated by the current time (calendar year). Historical factors represent the influence of the past on current behavior or experience, and are usually referred to as ‘cohort effects’. These occur whenever events in the past have a lasting impact that is felt by most people of the same age range (contemporaries, generation). The method of analysis employed to disentangle contemporary and historical factors is age-period-cohort (APC) analysis.

This work continues and extends a study conducted by Willekens and Scherbov (1991; 1992) where a similar approach was used to study mortality in the former Soviet republics without disaggregation by causes of death.

The following section describes the sources of mortality data in the former Soviet Union, and includes a description of the data collection process (registration system) and a discussion of the quality of data. Section 3 reviews the APC model, including a brief history of APC analysis in mortality, and presents the statistical theory underlying the APC model. Section 4 presents the results of the APC analysis and discusses the contribution of historical and contemporary factors to mortality changes by cause of death in 12 republics of the former USSR. The trend analysis constitutes a basis for a scenario of future mortality. This scenario, presented in Section 5, is moderately optimistic and assumes that the former USSR will escape a social catastrophe. Section 6 concludes the analysis of mortality trends in the former USSR. A large set of tables and figures are included in the appendices.

2. Mortality data

Data on mortality by cause of death within the period of our consideration were based on doctors’ verification or medical assistants’ death certificates. The latter were common in urban areas, where most of the medical help was provided not by a medical doctor but by a medical assistant.

The death registration system functions in the following manner: a death certificate is issued by a doctor (medical assistant) to the relatives of the deceased (or to some person close to the deceased). They register the death at the civil registration office. Only the death of a baby younger than six days is registered by medical personnel.[2] Obviously with such a registration system, under-accounting of deaths occurs mostly at the youngest and oldest ages, especially in the muslim regions.

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[2] The Soviet definition of live birth and infant death differed from the one recommended by WHO and used in developed countries: by Soviet definition those babies who have been in gestation less than 28 weeks or are born weighing under 1000 g and die in less than seven days were excluded from live birth. Russia adopted the WHO definition on January 1, 1993.

The proportion of autopsies, especially in rural areas, was not high, but in muslim regions (Central Asia, Azerbaijan, part of Kazakhstan, North Caucasus in the Russia Federation and some other regions of Russia) it was almost negligible. In the Russian Federation it made up 33 percent.

A medical doctor or medical assistant identified the cause of death according to the patient's medical history. But if the time period between the last examination and death was long enough, then the cause of death was determined according to the symptoms described by relatives. Under such circumstances the quality of diagnostics could not be high and most of the researchers used data by wide groups of causes of death.

A number of local studies (Nicolskiy 1979; Ministry of Public Health of Russian Federation (Minzdrav RSFSR) 1981) prove substantial over-diagnosis of the most common diseases and primarily of all circulatory diseases. At the same time there was an under-diagnosis of infectious diseases, particularly for children, because high mortality from digestive infections was regarded as a drawback of the health care system.

Another paradoxical example: In order to improve the indicators of activity in oncology clinics, in many regions of the country, cancer was diagnosed only for those deceased who were registered in the oncology clinics.

Another source of error appeared during the encoding of data on mortality by cause of death. The combination of less-qualified people responsible for encoding the data, together with inaccurate initial records (sometimes as a result of an overworked doctor making the report) led to an over-accounting of the most common causes of death. Perhaps that is why the proportion of deaths from numerous chronic diseases (of the endocrine system, of the urine-genital system, etc.) in the USSR was relatively low in comparison with developed countries.

Another aspect of the problem concerns data on population size. In the USSR population size was estimated year by year starting with the last census. The data collected were annual number of births, deaths and migration between republics. But often these data were inaccurately counted which led to an accumulation of errors. They were manifested in discrepancies between the next census results and the results of estimation. Census accuracy is also not ideal, but the census results are in general more realistic except perhaps for the mobile age groups (16-24 years of age). Because of this, there was a revision of intercensus data on population after each census. However, no adjustments of mortality and fertility indicators were conducted as a rule.

In our study we used mortality rates by cause of death, evaluated in the Department of Demography of the Institute of Statistics and Economic Studies of the Russian State Committee on Statistics (these data were partly published in State Committee of the USSR on Statistics 1988; State Committee of the USSR on Statistics 1989; State Committee of the USSR on Statistics 1991). A special issue with statistical data was planned to be published but failed due to the dissolution of the USSR.

Evaluation of mortality rates is based upon the data from the state statistics on mortality for 1980-1990 and the data on population size for the beginning and end of each year. Data on population size for 1980-1988 were adjusted using the results of the 1989 census.

Until 1982 data on mortality by cause of death were classified according to the 7th ICD of WHO. After 1982 classification of mortality by cause was made using the 8th ICD revision. In the grouping of causes of death used in our paper (diseases of the circulatory system; neoplasms; accidents, poisonings and violence; diseases of the respiratory system;

infectious and parasitic diseases; diseases of the digestive system and a group of all others and unknown causes) the change in ICD revision denoted that in 1980 and 1981 part of those deaths that later on would be classified as deaths from infectious diseases were classified as deaths from diseases of the digestive system.

First, we considered re-estimating mortality rates for 1980-1981 according to the 8th ICD revision. But we found that the transition to the new ICD revision was not immediate. Virtually in 1982-1986 and perhaps even later, a part of the infectious diseases of the digestive system continued to mask under the diseases of the digestive system. At least from the further analysis of the dynamics of period effects for deaths from diseases of the digestive system and infectious diseases, one can obtain no discontinuity related to the adoption of the new ICD revision. We therefore rejected re-estimation of mortality rates for 1980-1981.

3. The age-period-cohort (APC) models[3]

3.1. Introduction

The cohort or generation is an important concept in the study of changes in human behavior and experiences over time. The interest in cohort analysis is particularly large when discontinuities occur in trends. Cohort analysis is expected to reveal and quantify the impact in time of these discontinuities. Mannhein, who introduced the generation concept into sociology in 1928, ascribed growing interest in the generation problem to political discontinuities in the late 19th century. The trends that are studied may relate to social, economic, demographic, health or other variables. As a consequence, cohort analysis is broadly applied. For a general review covering several disciplines, see Hastings and Berry (1979). Hobcraft et al. (1985) review demographic studies; Breslow (1985) and Lidell (1985) discuss cohort analysis in epidemiology; Baltes et al. (1979) address cohort studies in psychology and Attias-Dunfot (1988) presents a comprehensive treatment of the cohort (generation) concept and generation theories in sociology (with at least one major omission, namely the classical article by Ryder 1965).

In traditional APC analysis, the contemporary factors are approximated by the current period, and the historical factors are represented by the year or period of birth. Current period and period of birth are not causal factors in the analysis. They are crude indications of the macrosetting that changes over time and in which demographic phenomena are embedded. In the traditional analysis, the demographic rates, measured for a given age group during a given period, are decomposed into an effect of age grouping (age effect), an effect of contemporary factors (period effect) and lasting effect of historical factors experienced by the group of people to which the rate applies (cohort effect). A (birth) cohort is generally defined as a group of people born during the same period; in APC analysis, it is interpreted as a group of people who lived through comparable historical or structural contexts (e.g. depression, war period, period of rapid technological change). They may be referred to as 'contemporaries'. Although the impact of past common experiences remaining at the time of observation is likely to differ for each member of the group, there is probably some effect that is still felt by all members of the group. That effect is the cohort effect. APC analysis attempts to unravel inter-cohort differences and intra-cohort variations.

The APC analysis combines the two viewpoints traditionally distinguished by a demographer when analyzing demographic data. One approach examines changes from year to year. Period analysis, as this approach is known, is particularly useful when rapid

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[3] This section is based on Willekens and Scherbov (1992).

changes occur, such as technological or legal changes that directly affect the controllability of demographic processes, or a war or a revolution resulting in transitory behavioral changes such as the postponement of births. The other approach, cohort analysis, is better suited for the study of fundamental changes in behavior such as an increase in health conditions and life expectancy. For a comprehensive treatment of APC analysis in demographic and social research, see Mason and Fienberg (1985).

The traditional APC model is not an explanatory model but a statistical accounting scheme. To interpret the period and cohort effects, one must look for attributes of the historical contexts that brought about the effects; the age effects must be related to attributes of human development over the life-span. The new approach to cohort or APC analysis introduces two major changes. First, it adopts a multilevel perspective: the characteristics of a cohort are aggregated outcomes of the individual behavior of cohort members in the societal and technological contexts. In other words, the effects of contemporary and historical factors on demographic change are <u>mediated</u> by individual characteristics, including the stage in the life course. Second, it adopts a <u>process perspective</u> and calls for longitudinal data to investigate the processes as they evolve.

Nowadays, dying is rarely a sudden event; it is usually the culmination of a lengthy process during which the individual has suffered to a greater or lesser degree from diseases or handicaps which affect his mortality risk. It is thus a complex process (morbidity), the conclusion of which (death) cannot be studied without taking into account the process which preceded it: the population distribution of morbidity is a prime determinant of mortality risks and in turn the selection effects of mortality determine who survives with a chronic degenerative disease (Van Poppel 1990, p.241).

The modern APC analysis is process-oriented and integrates life course analysis into cohort analysis. The integration signifies that events are simultaneously studied in two time scales: age and historical time. This approach is followed by Caselli and Wunsch among others (see e.g. Caselli et al. 1990).

3.2. APC Analysis of Mortality: A Brief History

Although the impact on mortality trends of intergenerational variations in health was recognized in the 1920s, it was not until the 1970s that the cohort perspective was more generally adopted for the analysis of mortality trends. In general, cohort analysis and APC analysis has been motivated by one of two questions. The first focuses on the regularity of observed patterns and is associated with descriptive research; the second emphasizes the underlying mechanisms causing the regularity and is mainly associated with explanatory and epidemiological research (Hobcraft et al. 1985 make the same distinction; see also Hobcraft & Gilks 1984). The two questions are the following:

a. Does an age distribution of a demographic phenomenon (e.g. mortality) exhibit a greater regularity when presented for a cohort than for a particular period? The age profile exhibited by period data confounds the effect of generational differences. This question is particularly relevant for demographic forecasting.

b. Do events and experiences early in life affect experiences later in life? In this perspective, cohort analysis derives its importance from the plausibility of biological mechanisms rather than from the use in forecasting.

According to Hobcraft et al. (1985, p.103), Derrick (1927) was the first to argue that cohorts provided a more consistent basis for projecting mortality than did period rates. The conclusion was based on a graphical examination of the logarithms of age-specific death rates for England and Wales from 1841 to 1925, omitting the experience of World War I, which indicated that the ratio of mortality for one cohort to that of another cohort was approximately constant for all ages above 10. Caselli and Capocaccia (1989), however, review a study published in 1912 by Mortana, in which he studied the presence of possible selection effects in infancy on mortality at old ages. Pollard (1987, p.58) lists studies which found that generation curves exhibit a greater degree of regularity. These studies are published in the 1920s and 1930s; in recent times, this regularity has not been observed to the same extent. Manton (n.d., p.31) reports that period mortality schedules tend to overestimate cohort mortality rates. This is particularly so when part of the cohort is eradicated by a war. Since relatively healthy persons are selected for active service, they suffer great losses, while less healthy people are more likely to survive. This adverse selection leads to an overestimation of true mortality some decades later (Dinkel 1985, p.95). The selection is also in effect when mortality is studied by cause of death.

Explanatory research into the mechanisms underlying changes in mortality patterns focus on the impact of early experience on subsequent behavior. Kermack et al. (1934), studying time series of death rates of England, Scotland and Sweden, argued that the cohort differences in mortality were not a consequence of a series of independent conditions affecting successively older ages; instead, the health of a cohort was principally determined by environmental conditions encountered in its first 15 years of life. The authors also found that improvements in early childhood mortality followed mortality improvements in ages of maternity. They argued that early childhood mortality was closely linked to the health and physique of mothers. Kermack et al. adopted the life course perspective on cohort analysis long before it became popular in the 1980s when individual-level data became available. Preston and Van de Walle (1978), studying French data, and Caselli and Capocaccia (1989), using Italian data, demonstrated a positive relation between infant and child mortality and adult or old-age mortality (weakening effect). Others, however, stressed that high infant and child mortality result in lower mortality at higher ages because of a selection effect (e.g. Manton et al. 1981).

The introduction of cohort analysis in public health is generally attributed to Andvord (1921; 1930) and Frost (1939), who showed that apparent changes in age-specific rates of mortality from tuberculosis (TB) could be viewed as translations of declining TB mortality across cohorts with a relatively constant age profile of TB mortality. The authors believed that the TB infection occurred early in life and that the disease has a highly variable incubation period, tending to the lengthy (see Mason & Smith 1985, p.155). This implies that differences in infection rates in childhood largely determine differences in cohort experience. The authors suggested that, in the absence of effective chemotherapy, successive cohorts moved through life as though they had different probabilities of dying from TB assigned at birth. McKeown (1976), who has carried out one of the most authoritative research into causes of decline in mortality from micro-organisms, argues in the case of TB that changes in the probabilities of dying from TB are preceded and caused by improved nutrition (for a discussion, see Mason & Smith 1985, p.156ff). A major contribution of the study was the demonstration that the age distribution of mortality from TB was constant (regular) in cohorts rather than in periods and that period analysis may lead to erroneous conclusions.

Case (1956) adopted a cohort perspective in the study of lung cancer in England and Wales for the period 1911-1954. The importance of cohort effects rested on the plausibility of biological mechanisms rather than on statistical tests. Case argued that the fact that successively younger cohorts were smoking cigarettes more heavily caused the cohort effects. Other references are listed in the bibliography and Appendix D.

A major research preoccupation of those European countries which were actively involved in World Wars I and II was examining the health and mortality situation at advanced ages of men who saw active service. The studies revealed two major findings. First, it has been shown in France, Italy and the Federal Republic of Germany that male cohorts which participated in World War I subsequently experienced higher mortality than adjacent cohorts who were not involved in the conflict. Second, in Italy and the Federal Republic of Germany, the same excess mortality has been detected among those who were born or were adolescent during the war years (Vallin 1973; Vallin 1984 (France); Horiuchi 1983 (Federal Republic of Germany); Caselli & Capocaccia 1989 (Italy); Caselli et al. 1986 (Italy and France)). Boleslawski (1985) found a similar impact of World Wars I and II in Poland. In France, no notable weakening of the cohorts born during the World Wars was found (Wilmoth et al. 1988, p.16). Anderson and Silver (1989) studied mortality data from the Soviet Union from 1958-59 to 1986-87 and found that males and females who were born during World War II and males who were adolescent during that time experienced significantly higher mortality as they aged than would have been expected on the basis of their age at a given time and the overall mortality conditions of the given period. The prolonged mortality effect on those who were adolescent during the war is attributed to the lasting effect of malnutrition on cardiovascular development (Horiuchi 1983).

Caselli (1990) reports a remarkable observation for Italy. Very high levels of excess male mortality are found in the late 1960s for cohorts born during or just before World War I. She speculates that better living conditions allow more individuals to survive and make them more resistant to death until around age 50 (Caselli 1990, p.239 and 245). In the Soviet Union, the rise in mortality of males in the working ages in the 1960s was attributed to World War II (Bedny and other Soviet scholars, quoted in Anderson & Silver 1989, p.477). Dinkel (1985) also suggested that the increase in male mortality in the 1960s might be attributed to the weakening effects of World War II. Anderson and Silver are reluctant for such an interpretation of the cohort mortality estimates because they can trace at most only 30 years of the mortality experience of any cohort (Anderson & Silver 1989, p.492).

3.3. Statistical Theory

The statistical theory of APC models is of a recent date. According to Hobcraft et al. (1985), the first properly identified APC model was specified by Greenberg et al. (1950). The age effects were parameterized through a beta distribution. The first author to make the linear identification constraint explicit was Beard (1963). Examples of APC analysis of mortality trends include Barrett (1973; 1980), Osmond and Gardner (1982), Osmond et al. (1982), Tu and Chuang (1983), Geddes et al. (1985), Mason and Smith (1985), etc. The state-of-the-art in the mid-1980s of the statistical theory of the APC model was discussed by several authors in the book edited by Mason and Fienberg (1985).

The application of an APC model to a time series of age-specific data raises a statistical problem, which is known as the identification problem and which received much attention in the literature. When the data are presented in an age-period table, as is common in APC studies, the cohort cannot unambiguously be identified. For instance, a 20-year old person who experiences an event in 1991, is born in 1970 or 1971. If the event occurs before the birthday, the person is born in 1970. The person belongs to the 1971 birth cohort, however, if the event occurs after the birthday. The cohort effect cannot uniquely be determined since the cohort is not properly measured. All that can be estimated is the difference between cohort effects. The problem is known as the identification problem. The identification problem is solved by equating two cohort effects or fixing a cohort effect to a given value (aliasing). Analogously, a person born in 1971 experiencing an event in 1991, may be either 19 years of age (if the event occurs before the birthday) or 20 years (if the event occurs after the birthday). If the data are arranged by year of occurrence of the event and year of birth, the age effect cannot be fully disentangled. The reason is not the linear relationship between age, period and cohort, as is suggested in most of the literature, but the inadequate measurement of age, period and cohort (see Willekens & Baydar 1986; Robertson & Boyle 1986; Osmond & Gardner 1989). The measurement problem may be demonstrated graphically with the Lexis diagram (see Appendix C). The identification problem may be removed by

a. proper measurement of the timing of the event (date of occurrence, date of birth and age),

b. combining ages, cohorts or periods such that the number of effects to be determined reduces compared to the number of observations,

c. imposing restrictions on the values of the parameters (identification specifications),

d. substituting the age, period and/or cohort variables by other (better) proxies of life cycle stage, contemporary factors and historical factors, respectively.

The first approach was used by Willekens and Baydar (1986) and Robertson and Boyle (1986). The second approach is adopted in this paper. The third approach is followed in much of the traditional APC analysis (for a review, see Willekens & Baydar 1986). The fourth approach is applied by Heckman and Robb (1985) and Blossfeld (1986) among others. The fourth approach is to be preferred if data permit.

In this paper, the APC model is presented as a special case of a generalized linear model (GLM). A similar approach was adopted by Willekens and Baydar (1986). The number of deaths is a random variable associated with a stochastic process. Model fitting consists of three interrelated steps, following McCullagh and Nelder (1983):

i. Model Selection (model specification or identification)

   The model relates the outcome of the random process to the parameters of the process. The outcome is the number of events (deaths) in a particular interval, or any function of number of events. In this paper, we study the trend in death rates, defined as the ratio of the numbers of deaths and population at risk. The number and types of parameters are determined by the type of data that are available. One parameter is associated with each age, cohort and period.

ii. Parameter Estimation

   Given the model, we have to estimate the parameters from the data and obtain some measure of the accuracy with which we have estimated them.

iii. Prediction

   Prediction is concerned with the outcome of the actual random variable. Prediction is commonly thought of in the context of forecasting a future value of a variable. However, prediction is wider in scope and is used to indicate that the value assigned to a random variable is to be determined.

3.4. Model Selection

Models that we select to represent the data belong to the family of generalized linear models. An important characteristic of GLMs is that they assume independent observations. In case of non-independence, the variances will be larger than in the case of independent observations. It is assumed that deaths are generated by a Poisson process, hence the observed numbers of deaths follow a Poisson distribution. The Poisson assumption is justified when the death rate is low. In that case, the Poisson distribution is an adequate approximation of the binomial distribution, which describes binary response data (e.g. deaths/survivors) (McCullagh & Nelder 1983, p.74). The assumption that the number of deaths is an outcome of a Poisson process, has become widely accepted in the literature and is implicit in the log-linear analysis of mortality rates (see e.g. Holford 1980; Laird & Olivier 1981; Frome 1983; with a discussion by Nelder 1984; Egidi et al. 1990).

The dependent variable is the death rate, which is the ratio of the number of deaths and the total duration during which the population is exposed to the risk of dying. Since the exposure varies with the death rate, both the numerator and the denominator of the death rate are random variables and are interdependent. The dependence complicates the analysis substantially. Therefore, it is generally assumed that the denominator is fixed, i.e. independent of the number of deaths. If the death rate is small, the assumption is realistic. For a discussion of the issue, see Hoem (1984, p.41ff) and Breslow and Day (1985, p.57).

A major problem in model selection is the choice of variables to be included in the systematic part of the model. The strategy adopted in this paper is to associate one parameter with each age, period and cohort category.

Let n_{xtc} denote the observed numbers of deaths of age x, period t and cohort c. Let N_{xtc} denote independent random variables having Poisson distribution with positive parameter λ_{xtc} . λ_{xtc} is the product of the death rate and the duration of exposure to the risk of dying in year t by individuals of age x and cohort c, which is assumed to be fixed (L_{xtc}). The true value consists of two components: a systematic component, predicted by the model to be specified, and a random component. To be precise, the random component must be separated into two parts. One is a part due to our ignorance, i.e. the absence of a complete observation; the other part is due to the fact that the outcome of any random process is inherently uncertain even if we have all the necessary data to predict the outcome. No distinction between the two parts is made in this paper.

Let λ_{xtc} denote the systematic component and ε_{xtc} the random component. The model is:

$$n_{xtc} = \lambda_{xtc} + \varepsilon_{xtc} \qquad (1)$$

with $E(n_{xtc}) = \lambda_{xtc}$
$E(\varepsilon_{xtc}) = 0.$

3.4.1. The Systematic Component

The parameter λ_{xtc} of the Poisson distribution is assumed to satisfy a model that is loglinear in a set θ of unknown parameters. One parameter is associated with each of the ages, cohorts and periods. The systematic component is

$$\lambda_{xtc} = L_{xct}\,\alpha_x\,\beta_t\,\tau_c \qquad (2)$$

where $\theta = \alpha_x, \beta_t, \tau_c$ and L_{xtc} is the duration of exposure assumed to be given. Model (2) is the multiplicative formulation of the log-linear model. The additive formulation is obtained by taking the natural logarithm of both sides. In that case, the ln of the dependent variable is linear in the parameters.

The unknown parameters must be determined from the data. That involves (i) writing the probability density of the outcomes of N_{xtc}, which gives the probability of observing any of the possible values of N_{xtc}, n_{xtc} say, given the model and data, and (ii) maximizing that probability. The maximum likelihood estimation of the parameters will be discussed after the presentation of the random component.

3.4.2. The Random Component

The independence and Poisson assumptions imply that the random variable N follows a Poisson distribution and that the probability of exactly One deaths in year t of persons of age x and cohort c, is given by the probability density function

$$Pr(N_{xtc}=n_{xtc}) = \exp[-\lambda_{xtc}]\lambda_{xtc}^{n_{xtc}}/n_{xtc}! \qquad (3)$$

The Poisson distribution (3) is a member of the family of exponential probability density functions (McCullagh & Nelder 1983). To show this, we rewrite (3) as follows

$$\Pr\,(N_{xtc}=n_{xtc}) = \exp\,[n_{xtc}\ln\lambda_{xtc} - \lambda_{xtc} - \ln n_{xtc}!] \qquad (4)$$

Since the Poisson distribution is a member of the exponential family and the logarithmic transformation of the systematic component is linear in the parameters θ, it is possible to estimate the parameters of the distribution by maximizing the likelihood of the parameters with respect to the observations on the random variable. We now proceed with the estimation.

3.5. Parameter Estimation

The parameters θ are estimated by maximizing the likelihood of the outcomes of the independent Poisson processes, given the model (2) and the data. Since the logarithm is a monotonous increasing function, maximization of the log-likelihood is equivalent to maximization of the original likelihood. For a single observation n_{xtc}, the contribution to the likelihood is $n_{xtc}\ln\lambda_{xtc} - \lambda_{xtc}$. The log-likelihood of a set of observed flows n_{xtc}, where each flow is the outcome of a Poisson process with parameter λ_{xtc} is:

$$L = \sum_{xtc}[n_{xtc}\ln\lambda_{xtc} - \lambda_{xtc} - \ln n_{xtc}!] \qquad (5)$$

The maximization is not affected by the last term of (5), which may therefore be omitted.

If the model would perfectly predict the outcome of N_{xtc}, i.e. the maximum likelihood estimates are equal to the observations themselves ($\lambda_{xtc} = n_{xtc}$ and $\varepsilon_{xtc} = 0$), the likelihood is the maximum achievable, which is generally finite. To evaluate the goodness of fit of the model, we compare the likelihood achieved by the current model to the maximum of the likelihood achievable (i.e. the likelihood achieved by the full model). The logarithm of the ratio is known as the scaled deviance (see e.g. McCullagh & Nelder 1983, pp.24–

25; GLIM Manual). The deviance is proportional to twice the difference between the log likelihoods:

$$S(n,\lambda) = -2 \ln [L(\lambda,n)/L(n,n)]$$

$$= 2 [\ln L(n,n) - \ln L(\lambda,n)]$$

Large values of S indicate low values of $L(\lambda,n)$ relative to the full model, increasing lack of fit. For the Poisson distribution, the deviance is

$$S(n,\lambda) = 2 \sum_{xtc} [n_{xtc} \ln (n_{xtc}/\lambda_{xtc}) - (n_{xtc} - \lambda_{xtc})] \quad (6)$$

If a constant term $\varnothing$, which is known as the nuisance parameter, is included in the model it is generally the case that $D(n,\lambda) = S(n,\lambda)$ so that

$$D(n,\lambda) = S(n,\lambda)\, \phi$$

may be written in the more usual form of the log-likelihood ratio which is often used as a test in the analysis of contingency tables

$$D(n,\lambda) = 2 \sum_{xtc} n_{xtc} \ln (n_{xtc} / \lambda_{xtc}) \quad (7)$$

In order to determine the unknown $\varnothing$ parameters with maximum likelihood, we need to maximize the log-likelihood function with respect to the parameters. This results in a set of normal equations which need to be solved for the unknown parameters. The GLIM package, which uses generalized weighted least square, was applied. The weights are inversely related to the variances of the estimates. The algorithm uses the Fisher's scoring method. If the model is log-linear, the scoring method and the Newton-Raphson method reduce to the same algorithm (McCullagh & Nelder 1983, p.33; Aitkin et al. 1989, p.324ff.).

3.6. Prediction

The most probable number of deaths that are consistent with the available data and the model are given by the expected values of the N_{xtc} which is λ_{xtc}. The expected death rate may be written as follows:

$$\lambda_{xtc}/L_{xtc} = \kappa\, \alpha_x\, \beta_t\, \tau_c \quad (8)$$

where the parameters are restricted

$\alpha_1 = 1$, $\beta_t = 1$ and $\tau_c = 1$.

Alternative restrictions may be used.

4. Pattern of recent mortality change

4.1. APC Analysis

The age-period-cohort model was applied to a time series of mortality rates by age, sex and cause of death for 12 former Soviet republics. The following groups of causes of death were selected: diseases of the circulatory system; neoplasms; accidents, poisonings and violence; diseases of the respiratory system; infectious and parasitic diseases; diseases of the digestive system and a group of all others and unknown causes. Data for each cause of death were processed separately. Data on male and female mortality were also processed independently.

The data were available for age groups of five years, for the years 1980 to 1990. Several specifications of the APC model were tested. The final model included the following effects:

- age (17 age groups: below 1, 1-4, 5-9,...75-79),
- period (11 calendar years 1980-1990),
- cohort (2 cohorts[4]: those born before 1941 and those born after),
- region (12 former Soviet republics), and
- interaction effect between age and region and between period and region.

The interaction effect between age and region allows to consider regional differences of age specific mortality; the interaction between period and region quantify regional differences in overall mortality trends.

Computational results of the model are shown in Figures 1-16 (later on all Figures refer to Appendix B if not specially denoted). In order to keep the graphical data presentation to manageable proportions, the republics were divided into two groups taking into account the similarity of the processes. In fact the majority of the republics with muslim population comprised the second group and with non-muslim population the first group.

The aim of trend analysis is to identify major trends and deviations from trends. Significant fluctuations should be separated from random fluctuations. Some of the short-term variations in mortality rates are removed if (i) the years are grouped and the APC model distinguishes a period or cohort parameter for each cluster of years instead of for each year, or (ii) the temporal variation in (annual) period effects is parameterized. To parameterize period effects, a trend model may be used. Short-term variations may also be removed by smoothing the data. Data smoothing should however not remove the peculiarity of the process studied.

To obtain a general evaluation of the APC model for each sex and group of causes of deaths we calculated the coefficient of determination (R2) - the share of variance of original data accounted by the APC model (Table la). This indicator reached the minimum value of 0.936 for males (diseases of the digestive system) and 0.921 for females (accidents, poisonings and violence), indicating a rather high quality of model approximation to empirical data. In general this estimate is close to similar estimates obtained by Anderson and Silver (1989).

Though the model accounted for 12 regions simultaneously, we found it informative to evaluate the accuracy of modelling regional data (Table la) using R-squared criteria for each .of the republics. The absolute minimum of this indicator constituted 0.759 (Tajikistan, male, diseases of the digestive system), followed by 0.771 (Tajikistan, female, diseases of the digestive system).

To evaluate the goodness of fit for each republic from all causes we introduced the following index of approximation:

$$I^r=\sum_{i=1}^{7}\frac{1}{R_i^0}R_i^r$$

where R_i^r is the determination coefficient for republic r and cause i and R_i^0 for all sets of republics and cause i. The best quality of approximation (Table 1b) was thus obtained for Russia, Ukraine and Byelorussia, the worst for the Central Asian republics (excluding Kirghizia) and Azerbaijan.

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[4] The length of the time series did not allow to introduce more cohorts.

Linear correlation coefficients of period effects and period life expectancy for each republic and sex are shown in Table 2. Only in Armenia is this indicator lower than 0.8, in more than half of the cases it is higher than 0.9 and in one-third of the cases it is higher than 0.95. This helps to draw the conclusion that estimated period effects describe mortality level almost as well as classic period life expectancy.

4.2. Discussion

The decade 1980-1990 was a period of major events in the former USSR: the Chernobil catastrophe, the earthquake in Armenia, the continuation and end of the Afghanistan war, ethnic conflicts, especially the Armenia-Azerbaijan conflict, and intensive political processes that led to the dissolution of the USSR. To what extent are some of these events reflected in the results of our analysis? Not too much. One can distinctly see only the earthquake in Spitak and the antialcohol campaign in 1985. The first event was distinguished by an enormous increase in mortality from accidents and injuries; the second resulted in mortality decrease.

Let us look at the results of the APC analysis presented in Figures 1-16. Each figure corresponds to a particular gender and cause of death. It contains six graphs: standardized regional effects, age effects for Russia, age effects for each of the republics relative to Russia's age effects, and period effects. Relative age effects and period effects are presented for each of the two groups of republics.

Russia n age effects were calculated by multiplying the age effects for Russia obtained from the APC model by the APC overall effect and regional effect for Russia. In the same way the age effects for the rest of the republics were obtained and later on they were divided by Russian ones to obtain relative age effects. Period effects were directly taken from the APC model. To evaluate standardized regional effects we used the above-described age effects and UN standard age distribution.

According to standardized regional effects which may serve as an indicator that averages mortality during the decade, males living in Russia and Turkmenia hold a "leading" position in overall mortality closely followed by males from Kazakhstan (a considerable part of whom are ethnic Russians). For females a "leading" position is kept by women living in Turkmenia followed by women from Tajikistan and Moldavia.

Examining age effects one can immediately understand why the males from Russia maintain the "leading" position in mortality. Starting from about 15 years of age (on the line graphs each data point corresponds to the age interval which lies to the right of that point) all republics have mortality age effects lower than the Russian ones, though at younger ages the situation in Russia is not so bad if compared to other republics. Age effect for the second age interval (1-4 years) in the second group which is comprised mostly of muslim republics in several cases is more than five times higher than in Russia.

Correlation of the period effects with time (trend model) allows us to estimate the mortality trend (Table 3). For all of the republics except Armenia this correlation is negative for all causes of death, which supports the general tendency in the decade towards mortality decline. The only republic whose correlation is positive is Armenia. But that is the result of the earthquake in 1988.

The decade is distinguished by a stable decline of mortality from most of the selected groups of causes of death except neoplasms, diseases of the circulatory system, and the group of all others and unknown causes. Mortality from diseases of the circulatory system showed a stable trend towards the growth in Armenia, and a distinct tendency towards decline in Russia, Ukraine and Moldavia. For females the stable growth was also observed in Uzbekistan. Mortality increase from neoplasms was observed in all the republics except Azerbaijan and Turkmenia. In Georgia and Tajikistan the general trend was not that clearly pronounced.

The natural trend of declining mortality from the causes of death defined by the group accidents, poisonings and violence is displayed for males in all the republics, except, apparently, Armenia, who experienced one jump in period effect in 1988. Russian males keep an exceptional “leadership” in deaths from this cause (Figure 7). For females, besides Armenia there was a slight growth in Turkmenia and stability in Byelorussia. Male mortality decline from diseases of the respiratory system was manifested in all the republics and from diseases of the digestive system everywhere except Tajikistan. Female mortality from diseases of the respiratory system also constantly declined. But in the trends in mortality from diseases of the digestive system the republics were divided. Pronounced decline was observed in Kazakhstan and increase in Kirghizia. Generally speaking, the graphs show the low level of diagnostics for this group of diseases.

Mortality increase from infectious and parasitic diseases was observed in Uzbekistan (though very inconsecutive) and in Turkmenia, where the mortality level from this group of causes of death is rather high. Somehow Turkmenia is located in the area of ecological catastrophe, and high mortality from this group of causes is obviously caused by the lack of clean water. However one should not neglect that the high mortality level from epidemic hepatitis is an artifact that reflects high mortality from chemical affection of the liver (e.g. in Moldavia).

Mortality from causes in the group of all others and unknown causes increased in general everywhere except Azerbaijan. But the dynamics of death rates in different age categories was so irregular that we refused attempts to make mortality projections for this group of causes (Figure 17).

For the regional feature of mortality dynamics a considerable concern is caused by the situation in Byelorussia and Ukraine. Rapid mortality increase from neoplasms and the causes that fall into the category all others and unknown causes may be associated with the consequences of the Chernobil catastrophe. However for a deeper conclusion a detailed regional analysis of mortality by 30-40 causes of deaths should be conducted. But this was not the aim of our study.

Mortality dynamics for males and females from each particular group of causes virtually coincide. This is confirmed by the correlation coefficients that comprise the diagonal in Table 4. Other correlations in Table 5 in most cases reflect trends that have been already identified. Attention may be attracted by the negative correlation of the mortality trend from infectious and parasitic diseases on the one hand and digestive system diseases on the other (-0.4 for males and -0.6 for females). In 1981 the USSR adopted nine revisions of ICD, and part of the deaths that were previously classified as digestive system diseases starting from that year had to be counted as infectious diseases that apparently did not happen synchronous.

In general a remarkable stability of the overall mortality level in respect to the endogenous impacts should be denoted in the USSR on the one hand and significant fluctuations of the mortality level from a particular cause such as infectious and parasitic diseases, digestive system diseases and the group of all others and unknown causes on the other.

Influenza and digestive infection epidemics are possible reasons of mortality fluctuations. Unfortunately we did not have the data on morbidity that in the USSR as well as in many other countries is unreliable. Therefore we decided to use an indirect indicator of epidemiological conditions in a region within the calendar year. This indicator is an index of mortality seasonal fluctuations. The index was evaluated as a mean relative deviation of monthly number of deaths within the year from the mean for 13 consecutive months that include as the 7-th the current month. Strictly speaking

$$I^t = \frac{1}{12}\sum_{i=1}^{12}\frac{M_i - \bar{M}_i}{\bar{M}_i}$$

where M_i - the number of deaths in i-th month, i= 1,2,...12.

$$\bar{M}_i = \frac{1}{13}\sum_{k=-6}^{6} M_{i+k}$$

where -1 should be regarded as December of the previous year, -2 November, etc. The values of i equal to 13, 14, .. etc. denote January, February, etc., of the subsequent year.

Tables 6 and 7 present correlation coefficients between the indexes of seasonable fluctuations and period effects for all former Soviet republics for each cause of death.

As one can observe from the table, the reasonable level of positive correlation is obtained for the group accidents, poisonings and violence and the group of diseases of the circulatory system. The first correlation to a high extent was predefined by the earthquake in Armenia. But it is not clear what were the real reasons that defined the mortality growth from accidents during the years of instability in monthly dynamics for females in Uzbekistan (correlation coefficient 0.62) or for males and females in Moldavia (correlation coefficients 0.49 and 0.66, respectively).

Seasonal increases in mortality in most of the European republics are strongly pronounced in increases in mortality from diseases of the circulatory system and less pronounced in mortality from respiratory system and infectious diseases. Correlations in the line for digestive system diseases suggest the absence of reliable information on digestive infections because that is the only reason that explains the high correlation of mortality from this group of causes of death with seasonal increases of mortality in Russia, Moldavia, Kazakhstan, Azerbaijan, Tajikistan, Georgia, Turkmenia and Uzbekistan.

To sum up, we can say that the obtained data prove the negative influence of influenza epidemics upon the level of mortality from diseases of the circulatory system, and bring doubt to the correct diagnoses of diseases of the digestive system and infections in a number of regions of the former USSR.

5. Mortality scenario

5.1. Introduction

When projecting mortality, one explicitly or implicitly uses a projection scenario. An analysis of mortality dynamics in the former USSR under conditions of grave economic, social and political crises may convince the researcher to concentrate his attention on the most recent three-year period and to build his projections on the assumption of a rising socio-economic cataclysm. But this type of research is rather useless.

Cautious projections could be elaborated by simply extrapolating current trends which may be justified if one needs to attract attention and to demonstrate that together with economic crises, a demographic crisis is also developing. But that was already understood in the West and in the former USSR.

In our case the projection precaution could not correspond to real mortality dynamics. If the critical tendencies could not be mastered in 1992 or at least in 1993, Russia and other former Soviet republics will be facing either a new totalitarian dictatorship or a civil war, or both. And to anticipate mortality trends in this situation would be worthless.

Thus we tried to build a moderately optimistic projection variant, by default assuming that the former USSR could escape social catastrophe. In our projection we tried to consider the whole period 1980-1990, and if we gave preferences to the most recent years, the weights for that data never point to more than twice as big as the weights for the period 1980-1985. The last assumption is an important element in building our projection scenario that would be further strictly formalized.

Another assumption in our projection scenario is to retain in the future common features in mortality trends for all former Soviet republics. That accompanies the hypothesis on preserving economic and demographic ties (freedom of movement, civilized interregional migration, marriages, etc.) between the former republics. In fact that is another side to our assumption on the possibility of escaping disastrous developments of events. A rapid break of interrepublican relations today, to our minds, may come as a result of social cataclysm or one of the main causes of such a tragedy.

Taking into account these two hypotheses we selected a projection algorithm. We tried to perform projections for each of the seven selected groups of causes of death, and then summed them up to obtain the overall mortality projection.

5.2. Selection of Projection Method

Having ten years of mortality dynamics data, successful projections were difficult using standard methods. From a statistical point of view, having data for a decade allows some justified conclusions on future mortality dynamics for not more than 2-3 years.

We had to find a numerical procedure that allowed us to use in our projections the similarity of the processes in all or at least in most of the republics. The standard methods, based on the approximation of the series by some function of time (linear, exponential, polynomial, etc.) with subsequent extrapolation did not allow us to implement this idea, though one can imagine a model where one set of parameters is common for all the republics and another set adds the specific features for each republic, thus implementing the hypothesis on a common for all regions' overall mortality dynamics with different starting conditions.

But in our analysis we decided, after a number of numerical tests, to use the following equation:

$$P^r_{t+1} = \sum_{i=0}^{k} a_i \, P^r_{t-i}$$

where $\mathbf{P}^r_t$ are the estimates of the period effects in year t and in region r, and a_i equation coefficients.

The use of a finite difference equation is equivalent to the hypothesis that dynamics of period effects are described by a differential equation of $k+1$ order. Taking into account the length of the time interval we selected an equation of the second order ($k=1$). It would be ideal to estimate parameters a_0 and a_1 simultaneously assuming that they are the same for all the republics. Another ideal situation would be to give no preferences for the time intervals within the decade of available data. But in this case we would ignore the real heterogeneity of mortality developments in the republics as well as real shifts in mortality trends. In practice that resulted in a big error of approximation in some cases compared to the levels of indicators with the maximum of the errors corresponding to the year 1990. Naturally that made the value of a projection doubtful.

Analysis of mortality dynamics showed that to reduce the errors of approximation and to obtain satisfactory results, it was sufficient to break down all the republics into two groups with six republics in each group (a slightly different subdivision was performed for mortality projections from the causes of death associated with accidents, poisonings and violence, but we will discuss this issue later on). One could find more sophisticated methods for grouping the republics, but under the risk of being called russia-centrists, we divided the republics into two groups by the similarity of the mortality process in each compared to the Russian republics (Table 8). To create the groups we used the distribution of correlation coefficients for period effects in each of the republics with Russia's period effect.

Another question: should all data for the period 1980-1990 equally participate in estimation of parameters a_1 and a_2? Can we claim that a scenario is good enough if the maximum approximation error corresponds to 1990? The idea to introduce weights is not a new one, but by manipulating the weights one may obtain any desirable result.

Thus we allowed for minimum and maximum weights to differ not more than twice. A natural assumption that the weights are growing with time was also accepted. The weights grew as a geometrical progression with a ratio selected from 1 to 1.1. A particular ratio was selected in the following way: We projected a period effect for the year 1990 using data for 1980-1989. Parameters a_0 and a_1 as well as a geometric progression ratio were obtained as least squares estimates (Figure 18).

After this procedure was defined we did no interference in order to fit the results of the projection to our own a priori judgment. The only group of causes of death where we did interfere was accidents, poisonings and violence, because data on mortality from the accidents for Armenia in 1988 should have been excluded from the model. We faced the problem of how to define the groups of republics for these specific causes, and where to allocate Armenia. Using our approach for the best approximation for 1990 we have chosen two unequal groups with seven and four republics and placed Armenia in the second group.

Mean relative errors of approximation series of $\mathbf{P}_t^r$ using a finite difference equation (Table 9) demonstrate high precision of fitting.

As one can observe from Tables 1 and 9, mortality from the group of causes "all others and unknown causes" is well described by the APC model and also gives good results in projections for 1990 based on 1980-1989 data. But at the same time this group of diseases is very heterogeneous. On the one hand, this group includes major causes of prenatal mortality and newborn anomalies, and on the other diseases of the urine-genital system, endocrine system, etc. Thus it could have been expected in advance that mortality projections for this group of causes would have com plications.

First of all mortality trends for younger ages (0-14) and older than 50 were very different. That forced us to repeat all calculations again but independently for both age categories. But even this did not simplify our job. As a matter of a fact in some of the republics considerable mortality increase from this group of causes of death was observed for the elderly only in 1990, and was not associated with previous history. In the other age groups mortality remained stable (Figure 17). Having too little information for any scientific conclusion in our projections we left mortality from this group of causes unchanged.

5.3. Results of the Projection

The results of our projections (Table 10) in general seem to look rather optimistic. For almost all the republics life expectancy will grow by the year 2000. At the same time in most non-muslim republics (Armenia, Byelorussia, Georgia, Moldavia, Ukraine) that comprise group 1, until 1995 infant mortality death rate is expected to increase (Tables 11 and 12). Between the other "notable" negative shifts we can indicate a mortality increase from neoplasms in the European republics and from diseases of the circulatory system in Central Asia.

The results in Tables 12 and 13 were obtained using methods of component analysis (Andreev 1982). Apparently the results (Table 13) are presented with too high precision. No one can project life expectancy with two numbers after the decimal point. But in this way one can better see the logic of projections.

To evaluate the dynamics of age-specific mortality rates let us examine Figures 19-30, where typical mortality curves are depicted. The projected decline in mortality from accidents, poisonings and violence logically extends age-specific trends in Europe as well as in Asia.

There is no disapproval of projected mortality dynamics from the most important group of causes of death - diseases of the circulatory system (Figures 21 -24), though some irregularity in female projected mortality for the age group 45-49 in Kazakhstan and Georgia attracts attention. But these are the consequences of a chosen method for projection (autocorrelation fluctuations).

Mortality increase from neoplasm in the European region (Figure 25) unfortunately very naturally extends real trends in all age cohorts. Decline of mortality from this group of causes in Asia (Figure 26) reflects the trend of period effects, and is not very distinct. Mortality decline from diseases of the respiratory system is explicit in all age groups both in the European and Asia n republics (Figures 27 and 28).

Mortality dynamics from the group digestive system diseases gives some optimism (which continues recent trends) in Moldavia, where mortality from this group of causes holds a substantial share in total mortality. Projected mortality from this group of causes in Asia (Figure 30) is subjected to fluctuations and as we mentioned earlier brings some skepticism for the quality of diagnostics. As far as infections are concerned (we did not show the picture), the mortality dynamics here are very similar to mortality from respiratory diseases.

5.4. What If Our Projection Comes True?

If our rather optimistic projection comes true, then Russia and Turkmenia will retain last place in male life expectancy (next in line at the bottom of the list will be Kazakhstan, where today life expectancy is less than in Russia, but due to rapid decline of exogenous mortality it may become higher) (Figure 31).

For females, in spite of a considerable increase, the lowest life expectancy will remain in Turkmenia and Moldavia (Figure 32). The males of Caucasus will keep ahead, as will the females of Georgia, Azerbaijan and Byelorussia.

The largest difference between male and female life expectancy (Figure 33) will remain in Russia, Ukraine, Byelorussia and Kazakhstan and the smallest will be in Uzbekistan and Tajikistan.

The map of dynamics of life expectancy (Figures 34 and 35) shows that the maximum growth in life expectancy could be anticipated in muslim republics, as a result of mortality decline from exogenous causes of death. The change in overall life expectancy may be decomposed into changes related to the various causes. Figures 36 and 37 show the changes in life expectancy between 1990 and 2000 that may be attributed to expected changes in mortality due to neoplasms. We do not expect a mortality increase due to neoplasms.

Considerable growth of life expectancy in 1960-70 in the West was associated with the decline of mortality from diseases of the circulatory system. Unfortunately, our optimistic projection does not yet predict any shifts in this direction (Figures 38 and 39).

6. Conclusion

The most recent data on mortality by sex and causes of death for the former Soviet republics were considered in the paper. A first attempt of applying an APC approach to these mortality data by cause of death showed the applicability of a chosen method for interpretation of mortality trends for our data. It was shown that despite the social tension in this country the mortality from most causes of death decreased, though the trends towards mortality decline within the period was uneven. The consequences of such events as the anti-alcohol campaign, the earthquake in Armenia and the Chernobil catastrophe were obtained as a result of our analysis.

For projection of mortality trends up to the year 2000 we assumed that no social or other global cataclysms will take place. Under this assumption we extrapolated mortality trends of the 1980s using an autoregressive model separately for each cause. Obtained results predict a general decline of mortality from most causes of death under consideration except neoplasms and chronic diseases that are included in the group “other causes”. Mortality from neoplasms showed stable increase. Due to extreme instability of mortality from the causes of death that comprise the group “others and unknown causes”, projection for this group was not performed, and for projection of mortality for all causes of death we took an unchanged level of mortality from this group of causes corresponding to the observed rates of 1990.

According to our projection, life expectancy in all of the former USSR republics except Armenia will increase by the year 2000 approximately by 1year for males and females. The maximum increase of life expectancy may be anticipated in the Central Asian republics as a result of mortality decline from exogenous causes of death.

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The 2016 Russian Demographic Data Sheet: Highlights and Comparison to Old Scenarios Published in 1988

1. Highlights from the 2016 Russian Demographic Data Sheet[1]

Stefanie Andruchowitz

Tables 1-2 give key indicators for all 8 Federal Districts.
Tables 3-11 give the rankings of regions listing each the top 5 and bottom 5 regions with the Russian Federation level of the indicator in the middle.

Table 1. Population change

Изменение численности населения	Численность населения на 1 января (тыс.)		Среднегодовые темпы изменения численности населения (%)		Population change
Учетный период	2016	2035	2010-2016	2016-2035	Reference period
Российская Федерация	**146 545**	**146 462**	**0,16***	**0,00**	**Russian Federation**
Центральный федеральный округ	39 104	40 072	0,33	0,13	Central Federal District
Северо-Западный федеральный округ	13 854	14 255	0,30	0,15	Northwestern Federal District
Южный федеральный округ	16 368	16 183	0,23*	-0,06	Southern Federal District
Северо-Кавказский федеральный округ	9 718	10 180	0,64	0,24	North Caucasian Federal District
Приволжский федеральный округ	29 674	27 917	-0,18	-0,32	Volga Federal District
Уральский федеральный округ	12 308	12 624	0,30	0,13	Ural Federal District
Сибирский федеральный округ	19 324	19 210	0,03	-0,03	Siberian Federal District
Дальневосточный федеральный округ	6 195	6 023	-0,33	-0,15	Far Eastern Federal District
	Population size as of January 1* (thousands)		**Annual rate of population change** (%)		

* без Республики Крым и г. Севастополь - without Crimea and Sevastopol

Note: **Population size**: In this data sheet, the resident population is presented for Russia and its subjects as of January 1st, 2016 and for projections as of January 1st, 2035. **Annual rate of population change**: the average annual rate of population change, measured as a %.

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[1] Figures are reprinted from Russian Demographic Data Sheet 2016. RANEPA, Rosstat, and IIASA: Moscow, Russia and Laxenburg, Austria. www.populationrussia.ru/eng/

Table 2. Population aging

Старение населения	Доля населения старше трудоспособного возраста (%)		Демографическая нагрузка пожилыми (%)		Population ageing
Учетный период	**2016**	**2035**	**2016**	**2035**	Reference period
Российская Федерация	**24,6**	**29,7**	**45,6**	**61,8**	**Russian Federation**
Центральный федеральный округ	26,8	32,1	49,4	66,5	Central Federal District
Северо-Западный федеральный округ	25,8	30,5	47,3	63,7	Northwestern Federal District
Южный федеральный округ	25,9	31,2	48,9	66,1	Southern Federal District
Северо-Кавказский федеральный округ	17,0	23,6	31,9	47,9	North Caucasian Federal District
Приволжский федеральный округ	25,2	31,0	47,5	66,3	Volga Federal District
Уральский федеральный округ	22,6	27,0	41,9	55,7	Ural Federal District
Сибирский федеральный округ	22,9	27,2	42,9	56,4	Siberian Federal District
Дальневосточный федеральный округ	21,6	25,4	39,0	50,1	Far Eastern Federal District
	Proportion of population above legal pension age, women 55+, men 60+ (%)		**Old-age dependency ratio** (%)		

Note: Proportion of population above legal pension age: The share of the population above the legal pension age - 55+ for women and 60+ for men. Old-age dependency ratio (OADR) men 60+/20-59, women 55+/20-54: This relates the number of people above legal pension age (men aged 60 and above, women aged 55 and above) to the number of people of working age (men aged 20-59, women aged 20-54). The old-age dependency ratio is often considered as a measure of aging and is used for rough estimates of labor force participation, provision and receipt of net transfers, health care costs, pension entitlements, etc. It is expected to rise sharply over the next 40 years. Since the old-age dependency ratio is based solely on chronological age, it has been shown that alternative measures should be included in the study of population aging (Sanderson & Scherbov 2005; Sanderson & Scherbov 2007; Sanderson & Scherbov 2010; Sanderson & Scherbov 2013).

Table 3. Number of women per 100 men for selected age groups, 2016

Число женщин на 100 мужчин для некоторых возрастных групп, 2016

Number of women per 100 men for selected age groups, 2016

	Ранг 60+	**60+**	**Ранг 70+**	**70+**	**Ранг 80+**	**80+**	
Ивановская область	1	216	2	308	3	416	Ivanovo oblast
Мурманская область	2	214	1	338	2	489	Murmansk oblast
Ярославская область	3	209	4	292	9	396	Yaroslavl oblast
Владимирская область	4	209	6	290	17	379	Vladimir oblast
Тульская область	5	207	9	288	23	368	Tula oblast
Российская Федерация		**184**		**244**		**310**	**Russian Federation**
Республика Саха (Якутия)	78	161	72	211	72	254	Republic of Sakha (Yakutia)
Республика Дагестан	79	138	82	157	80	167	Republic of Dagestan
Республика Ингушетия	80	137	81	161	82	133	Republic of Ingushetia
Чеченская Республика	81	135	80	166	81	155	Chechen Republic
Чукотский автономный округ	82	127	79	175	74	242	Chukotka autonomous area
	Rank 60+	**60+**	**Rank 70+**	**70+**	**Rank 80+**	**80+**	

Note: **Number of women per 100 men:** Total number of women per 100 men.

Table 4. Old-age threshold for selected regions


Порог старости для отдельных регионов
Old-age threshold for selected regions

Примечание: Указанные регионы ранжированы по значениям в 2015 году **Note:** Selected regions ranked by 2015 values

Note: **Old-age threshold**: The old-age threshold is a flexible threshold of who is considered old. It assumes that people do not become old on their 55th, 60th, or 65th birthday regardless of time, place of residence, their health, and other characteristics. Instead, the old-age threshold depends on the characteristics of people (Kudrin & Gurvich 2012; Sanderson & Scherbov 2005; Sanderson & Scherbov 2007; Sanderson & Scherbov 2010; Sanderson & Scherbov 2013; Shoven 2008). In this data sheet the old-age threshold is the age at which the average remaining life expectancy first falls below 15 years.

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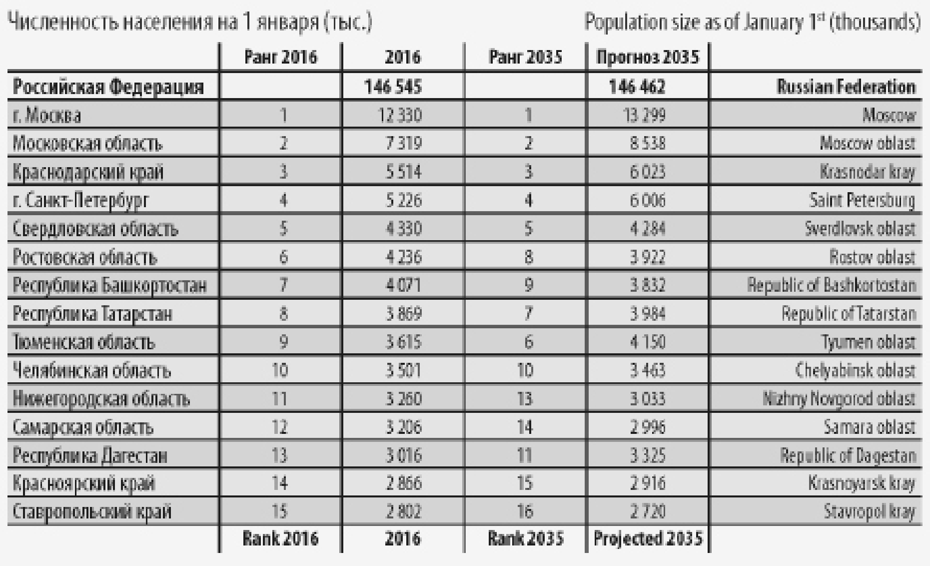
Table 5. Population size as of 1 January



Численность населения на 1 января (тыс.) — Population size as of January 1^{st} (thousands)

	Ранг 2016	2016	Ранг 2035	Прогноз 2035	
Российская Федерация		**146 545**		**146 462**	**Russian Federation**
г. Москва	1	12 330	1	13 299	Moscow
Московская область	2	7 319	2	8 538	Moscow oblast
Краснодарский край	3	5 514	3	6 023	Krasnodar kray
г. Санкт-Петербург	4	5 226	4	6 006	Saint Petersburg
Свердловская область	5	4 330	5	4 284	Sverdlovsk oblast
Ростовская область	6	4 236	8	3 922	Rostov oblast
Республика Башкортостан	7	4 071	9	3 832	Republic of Bashkortostan
Республика Татарстан	8	3 869	7	3 984	Republic of Tatarstan
Тюменская область	9	3 615	6	4 150	Tyumen oblast
Челябинская область	10	3 501	10	3 463	Chelyabinsk oblast
Нижегородская область	11	3 260	13	3 033	Nizhny Novgorod oblast
Самарская область	12	3 206	14	2 996	Samara oblast
Республика Дагестан	13	3 016	11	3 325	Republic of Dagestan
Красноярский край	14	2 866	15	2 916	Krasnoyarsk kray
Ставропольский край	15	2 802	16	2 720	Stavropol kray
	Rank 2016	**2016**	**Rank 2035**	**Projected 2035**	

Note: **Population size**: In this data sheet the resident population is presented for Russia and its subjects as of January 1st, 2016 and for projections as of January 1st, 2035. **Population projections**: Estimates of future population size and its composition based on assumptions about future trends in fertility, mortality, and migration. Projections in this data sheet are computed using the cohort component method and are based on two migration scenarios, that is, with and without migration (zero migration scenario) in addition to a scenario for fertility and mortality.

Table 6. Population median age

Медианный возраст населения (в годах) Population median age (years)

	Нестандартизованный				Стандартизованный		
	Ранг 2016	2016	Ранг 2035	Прогноз 2035	Ранг 2035	Прогноз 2035	
Тамбовская область	1	43,3	7	47,2	8	44,0	Tambov oblast
Тульская область	2	42,8	4	47,7	6	44,1	Tula oblast
Рязанская область	3	42,6	21	46,5	17	43,0	Ryazan oblast
Пензенская область	4	42,2	2	48,1	3	44,7	Penza oblast
Псковская область	5	42,2	11	47,1	22	42,8	Pskov oblast
Российская Федерация		**38,8**		**44,3**		**40,9**	**Russian Federation**
Республика Саха (Якутия)	78	32,5	79	34,3	80	30,9	Republic of Sakha (Yakutia)
Республика Дагестан	79	29,5	77	36,6	74	34,5	Republic of Dagestan
Республика Тыва	80	28,2	82	28,0	82	21,1	Republic of Tuva
Республика Ингушетия	81	27,7	80	33,6	78	32,3	Republic of Ingushetia
Чеченская Республика	82	25,5	81	28,4	81	25,7	Chechen Republic
	Rank 2016	2016	Rank 2035	Projected 2035	Rank 2035	Projected 2035	
	Non-standardized				Standardized		

Note: **Population median age**: The age that divides a population into two numerically equal groups, with half of the people being younger than this age and half older. **Population median age standardized**: In this data sheet the standardized median age (also called prospective median age) is the age in 2015, where remaining life expectancy is the same as at the median age in 2035. For example, in Russia life expectancy at median age is 44.6 in 2035, the same as at age 41.2 in 2015. In this data sheet we look at both sexes combined.

Table 7. Life expectancy at birth, 2015

Ожидаемая продолжительность жизни при рождении (в годах), 2015 Life expectancy at birth (years), 2015

	Ранг мужчины	Мужчины	Ранг женщины	Женщины	
Республика Ингушетия	1	76,5	1	83,0	Republic of Ingushetia
Республика Дагестан	2	73,2	3	79,5	Republic of Dagestan
г. Москва	3	73,0	2	80,4	Moscow
Чеченская Республика	4	70,4	38	76,4	Chechen Republic
Карачаево-Черкесская Респ.	5	69,9	6	78,7	Republic of Karachaevo-Cherkessia
Российская Федерация		**65,9**		**76,7**	**Russian Federation**
Амурская область	78	61,6	78	73,3	Amur oblast
Иркутская область	79	61,3	76	73,5	Irkutsk oblast
Чукотский автономный округ	80	59,4	81	69,7	Chukotka autonomous area
Еврейская автономная область	81	59,1	80	71,5	Jewish autonomous oblast
Республика Тыва	82	58,1	82	68,3	Republic of Tuva
	Rank male	Male	Rank female	Female	

Note: **Life expectancy at birth**: The average number of years a newborn would live if subjected to the age-specific mortality rates of a given period for his/her entire life.

Table 8. Difference between female and male life expectancy at birth and total fertility rate

Разница между женской и мужской продолжительностью жизни при рождении (в годах)
Difference between female and male life expectancy at birth (years)

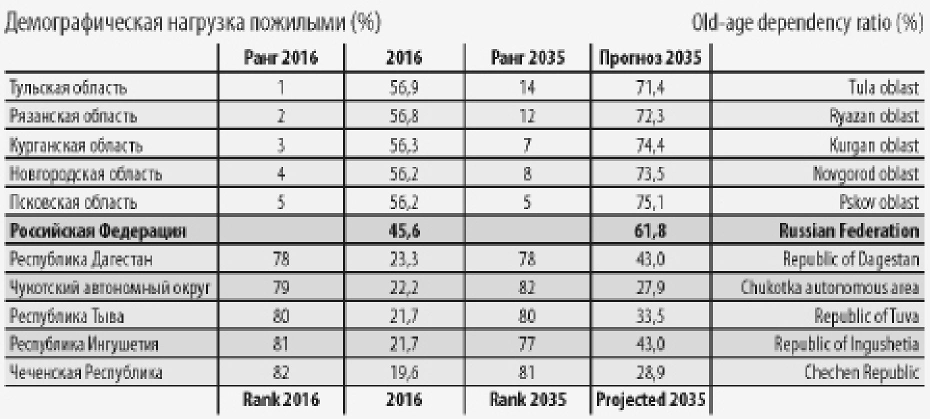
	Ранг	2015	
Орловская область	1	12,9	Oryol oblast
Республика Марий Эл	2	12,8	Republic of Marly El
Курганская область	3	12,7	Kurgan oblast
Республика Карелия	4	12,6	Republic of Karelia
Новгородская область	5	12,5	Novgorod oblast
Российская Федерация		**10,8**	**Russian Federation**
г. Санкт-Петербург	78	8,6	Saint Petersburg
г. Москва	79	7,4	Moscow
Республика Ингушетия	80	6,5	Republic of Ingushetia
Республика Дагестан	81	6,3	Republic of Dagestan
Чеченская Республика	82	6,1	Chechen Republic
	Rank	**2015**	

Суммарный коэффициент рождаемости
Total fertility rate

	Ранг	2015	
Республика Тыва	1	3,39	Republic of Tuva
Чеченская Республика	2	2,80	Chechen Republic
Республика Алтай	3	2,68	Republic of Altai
Республика Бурятия	4	2,28	Republic of Buryatia
Республика Саха (Якутия)	5	2,19	Rep. of Sakha (Yakutia)
Российская Федерация		**1,78**	**Russian Federation**
Воронежская область	78	1,52	Voronezh oblast
Тамбовская область	79	1,51	Tambov oblast
г. Москва	80	1,41	Moscow
Республика Мордовия	81	1,36	Republic of Mordovia
Ленинградская область	82	1,29	Leningrad oblast
	Rank	**2015**	

Note: **Life expectancy at birth**: The average number of years a newborn would live if subjected to the age-specific mortality rates of a given period for his/her entire life. **Total fertility rate (TFR)**: The average number of children that would be born alive to a woman during her lifetime, if age-specific fertility rates of a given year remained constant during her reproductive years. It is computed as the sum of fertility rates by age across all childbearing ages: 15 to 50.

Table 9. Old-age dependency ratio



Демографическая нагрузка пожилыми (%)
Old-age dependency ratio (%)

	Ранг 2016	2016	Ранг 2035	Прогноз 2035	
Тульская область	1	56,9	14	71,4	Tula oblast
Рязанская область	2	56,8	12	72,3	Ryazan oblast
Курганская область	3	56,3	7	74,4	Kurgan oblast
Новгородская область	4	56,2	8	73,5	Novgorod oblast
Псковская область	5	56,2	5	75,1	Pskov oblast
Российская Федерация		**45,6**		**61,8**	**Russian Federation**
Республика Дагестан	78	23,3	78	43,0	Republic of Dagestan
Чукотский автономный округ	79	22,2	82	27,9	Chukotka autonomous area
Республика Тыва	80	21,7	80	33,5	Republic of Tuva
Республика Ингушетия	81	21,7	77	43,0	Republic of Ingushetia
Чеченская Республика	82	19,6	81	28,9	Chechen Republic
	Rank 2016	**2016**	**Rank 2035**	**Projected 2035**	

Note: Old-age dependency ratio (OADR) men 60+/20-59, women 55+/20-54: see Table 2.

Table 10. Prospective old-age dependency ratio

Перспективная демографическая нагрузка пожилыми (%) Prospective old-age dependency ratio (%)

	Ранг 2016	2016	Ранг 2035	Прогноз 2035	
Псковская область	1	28,9	1	36,0	Pskov oblast
Новгородская область	2	27,6	3	34,7	Novgorod oblast
Тверская область	3	27,4	6	33,7	Tver oblast
Тульская область	4	27,0	18	31,2	Tula oblast
Курганская область	5	26,5	2	35,6	Kurgan oblast
Российская Федерация		**18,8**		**26,2**	**Russian Federation**
Республика Саха (Якутия)	78	9,3	76	17,0	Republic of Sakha (Yakutia)
Тюменская область	79	9,3	78	16,7	Tyumen oblast
Республика Дагестан	80	8,2	79	15,0	Republic of Dagestan
Чеченская Республика	81	7,2	81	12,2	Chechen Republic
Республика Ингушетия	82	5,8	80	12,7	Republic of Ingushetia
	Rank 2016	2016	Rank 2035	Projected 2035	

Note: **Prospective old-age dependency ratio (POADR)**: This is based on a flexible threshold of who is considered old. It is calculated as a ratio of the number of people older than the old-age threshold to the number of people between age 20 and the old-age threshold.

Table 11. Proportion of population above old-age threshold

Доля населения в возрастах превышающих порог старости Proportion of population above old-age threshold

	Доля населения в возрастах превышающих порог старости* (%)				Доля населения старше трудоспособного возраста (%)				
	Ранг 2016	2016	Ранг 2035	Прогноз 2035	Ранг 2016	2016	Ранг 2035	Прогноз 2035	
Псковская область	1	19,3	1	21,5	4	29,0	6	34,4	Pskov oblast
Тверская область	2	18,4	7	20,3	6	28,7	14	33,4	Tver oblast
Новгородская область	3	18,4	6	20,5	5	28,7	16	33,3	Novgorod oblast
Тульская область	4	18,4	12	19,7	1	29,9	8	34,1	Tula oblast
Курганская область	5	17,7	3	20,6	14	27,9	21	32,8	Kurgan oblast
Российская Федерация		**13,1**		**16,2**		**24,6**		**29,7**	**Russian Federation**
Республика Саха (Якутия)	78	7,0	77	10,4	77	15,8	79	20,5	Republic of Sakha (Yakutia)
Тюменская область	79	6,9	76	10,6	76	16,2	76	22,2	Tyumen oblast
Республика Дагестан	80	5,1	78	9,4	79	12,8	77	21,8	Republic of Dagestan
Чеченская Республика	81	4,1	82	7,1	82	9,6	82	14,5	Chechen Republic
Республика Ингушетия	82	3,4	81	7,7	80	11,3	78	20,8	Republic of Ingushetia
	Rank 2016	2016	Rank 2035	Projected 2035	Rank 2016	2016	Rank 2035	Projected 2035	
	Proportion of population above old-age threshold* (%)				Proportion of population above legal pension age, women 55+ and men 60+ (%)				

* **Примечание:** Доля населения со средней ожидаемой продолжительностью жизни менее 15 лет
Note: Proportion of population that has an average remaining life expectancy of 15 years or less

Note: **Proportion of population above old-age threshold**: The share of the population with an average remaining life expectancy below 15 years. **Proportion of population above legal pension age**: The share of the population above the legal pension age, age 55+ for women and 60+ for men.

2. New insights from comparing the 2016 Russian Demographic Data Sheet to population scenarios for the USSR published by Scherbov & Lutz in 1988

Dalkhat M. Ediev

Demographers are naturally more concerned with the current state and future (projected) developments of the population than the histories. As part of this future-oriented stance, we rarely revisit our earlier ("outdated") projections which are no longer relevant to the current reality (with important exceptions [e.g., Keyfitz 1982; Keilman 1997; Keilman 1998; Khan & Lutz 2008; Long 1992]). Yet, revisiting "Future regional population patterns in the Soviet Union: Scenarios to the year 2050" (Scherbov & Lutz 1988) in the light of more recent population estimates and projections for the states of the former USSR offers interesting novel insights into the demographic prospects of the large Eurasian area and highlights the need to further advance modern demographic projection methodology.

In their novel and, at the time, methodologically advanced inquiry, Scherbov and Lutz carefully analyzed population trends in the republics (now, independent states) of the then Soviet Union and offered projections based on three scenarios:

- Scenario A. "Continued diversity": fertility and mortality remain at levels observed in 1985 (for migration, all scenarios rely on rates fixed at the baseline level).
- Scenario B. "Continued diversity in fertility; convergence in mortality": fertility rates remain at 1985 levels, while life expectancy gradually increases to 75.0 in all republics by 2020, and remains constant thereafter.
- Scenario C. "Convergence in fertility and mortality": life expectancy increases gradually to 75.0 and fertility goes to the replacement level in all republics by 2020, both remaining constant thereafter.

It was clearly not possible in 1988 to foresee the demographic troubles that started in early 1990s across the former USSR. It is not surprising that the population levels projected by Scherbov and Lutz are much higher than the present levels or their current projections. The Russian Demographic Data Sheet (RANEPA et al. 2016), a recent project led by Sergei Scherbov, for example, estimates the current (as of 2016) population size of Russia as 146.5 million and projects it to stay at the same level by 2035. Interpolated results from Scherbov & Lutz (1988) to these years (Table 1) are 6.6 to 21.7 million higher in 2016 and 14.2 to 39.0 million higher in 2035. The longer-term population deficits as compared to 1988

Table 1. Estimates and projections of the population size of Russia based on the Russian Demographic Data Sheet (RANEPA et al. 2016) and Scenarios (A to C) from (Scherbov & Lutz 1988), in millions

Year	Datasheet	Scenario A	Scenario B	Scenario C
2016	146.5	153.2	154.1	168.3
Datasheet deficit as compared to Scherbov and Lutz (1988)		6.6	7.6	21.7
2035	146.5	160.7	162.2	185.5
Datasheet deficit as compared to Scherbov and Lutz (1988)		14.2	15.7	39.0

projection (9.7-29.7% in relative terms) provide rough estimates of demographic losses due to the current demographic crisis in Russia.

The demographic price of the rapid socioeconomic and political transformations of the 1990s may also be assessed by comparing the Scherbov-Lutz projections to a "fast recovery" scenario (in Ediev 2001) where fertility goes – similar to the Scenario C – to the replacement level after the 2020s, although with a preceding period of higher fertility and with an eventually higher life expectancy (around 75 in 2020 as in the Scenario C but further gradually increasing to 80 by 2050). The "fast recovery" scenario brought the projected population size to above 160 million in 2050 and, eventually, to the stationary level of less than 170 million – both considerably lower than 185.5 million by 2050 depicted in scenario C.

Another account of demographic reality departing from what was envisaged in the late 1980s is presented in Figure 1, which features population trends according to the projections by Scherbov and Lutz as compared to the Russian Demographic Data Sheet and the recent UN World Population Prospects (UN Population Divsion 2017). As is clear from the patterns presented, the Scherbov-Lutz scenarios did well until the early 1990s when socioeconomic and political turmoil brought about rapid fertility decline, surging mortality rates (especially at younger working ages and more so for males) and also increasing migration to Russia from the rest of the former Soviet Union. It is hard to definitively point to which of those factors contributed what to the trend errors of the Scherbov-Lutz projection scenarios after the collapse of the USSR. The projection bias in the case of the whole USSR (right-hand panel in Figure 1) points to the role of factors other than migration, although a narrower gap in the case of Russia highlights the role of increased migration to that country. The relatively high levels of fertility assumed by Scherbov and Lutz (close to or considerably above the replacement level) are in contrast to the stark fertility falls across the former Soviet Union in the 1990s (to as low as 1.16 in Russia). We may single out the projection errors in the fertility

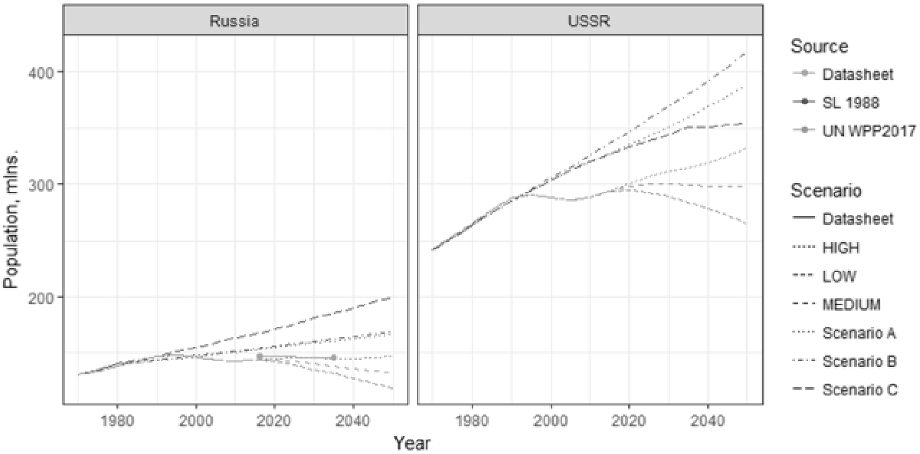


Figure 1. Population trends for Russia (left panels) and the former USSR (right panels) according to estimates and projections by Scherbov and Lutz (1988,"SL 1988") – scenarios A to C; the Russian Demographic Data Sheet (RANEPA et al. 2016,"Datasheet"), points connected by line; and UN World Population Prospects (UN Population Divsion 2017) – scenarios HIGH, LOW, MEDIUM.

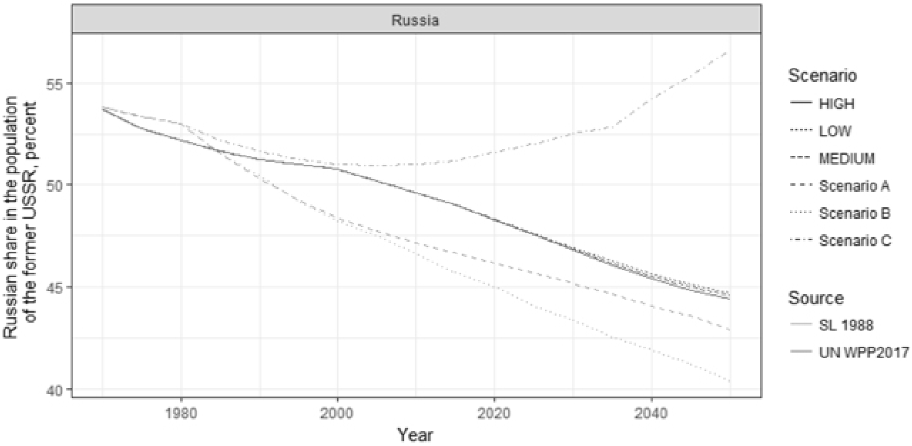


Figure 2. Share of Russian Federation in the population of the former USSR (percent) according to estimates and projections by Scherbov and Lutz (1988,"SL 1988") – scenarios A to C; and UN World Population Prospects (UN Population Divsion 2017) – scenarios HIGH, LOW, MEDIUM.

levels as the most influential factor of prediction failures of the 1988-based projection of current population size of Russia and of the former Soviet Union.

Although the population sizes projected in 1988 may be of limited relevance today, an interesting feature of the scenarios by Scherbov and Lutz is that they explicitly account for possible demographic divergence/convergence processes that may have reshaped the *population structure* of the former USSR. The projected structural changes may be more robust and resilient to changing reality given that the transformation shock has hit all of the former USSR. It is interesting to compare the structural developments projected by Scherbov and Lutz to population changes that have happened since then and current population projections (Figure 2).

Two striking patterns emerge from the comparison in Figure 2. First, despite the profound and unanticipated demographic shocks of the recent decades, scenarios by Scherbov and Lutz performed fairly well in terms of the population shares, especially Scenario C which assumed convergence of fertility and mortality across the former USSR (first of all, between Russia and the higher-fertility Central Asian soviet republics). Surprisingly, the demographic crisis that lowered fertility in Central Asia together with high migration from there to Russia and, apparently, the recent fertility recovery in Russia – all these factors brought the former soviet republics closer to the convergence Scenario C. UN scenarios seem to depart from Scenario C towards the more conservative Scenarios A and B. Those scenarios, however, may lack realism if the economic advantage of Russia over other (first of all, the Central Asian) republics continues to cause persistent migration flows and the Russian fertility recovery strengthens. In any case, it is amazing to see that the old Scherbov-Lutz projections are providing a realistic range of uncertainty for the relative population sizes in the former soviet area.

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