International Institute for Applied Systems Analysis

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Population momentum and the demand on land and water resources

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SUMMARY

Future world population growth is fuelled by two components: the demographic momentum, which is built into the age composition of current populations, and changes in reproductive behaviour and mortality of generations yet to come. This paper investigates, by major world regions and countries, what we know about population growth, what can be projected with reasonable certainty, and what is pure speculation. The exposition sets a frame for analysing demographic driving forces that are expected to increase human demand and pressures on land and water resources. These have been contrasted with current resource assessments of regional availability and use of land, in particular with estimates of remaining land with cultivation potential. In establishing a balance between availability of land resources and projected needs, the paper distinguishes regions with limited land and water resources and high population pressure from areas with abundant resources and low or moderate demographic demand. Overall, it is estimated that two-thirds of the remaining balance of land with rainfed cultivation potential is currently covered by various forest ecosystems and wetlands. The respective percentages by region vary between 23% in Southern Africa to 89% in South-Eastern Asia. For Latin America and Asia the estimated share of the balance of land with cultivation potential under forest and wetland ecosystems is about 70 percent, in Africa this is about 60%. If these were to be preserved, the remaining balance of land with some potential for rainfed crop cultivation would amount to some 550 million hectares. The regions which will experience the largest difficulties in meeting future demand for land resources and water, or alternatively have to cope with much increased dependency on external supplies, include foremost Western Asia, South-Central Asia, and Northern Africa. A large stress on resources is to be expected also in many countries of Eastern, Western and Southern Africa.

1. INTRODUCTION

There are three major institutions that publish worldwide population projections: the United Nations Population Division, the US Bureau of the Census and the International Institute for Applied Systems Analysis (IIASA). In the following analyses we will only use the most recent edition of the UN Population Assessments and Projections, which was completed in November 1996. These UN projections have not been officially published at the time of writing—but we had access to an internal data compendium ('Annexes I and II') that will be included in the official publication. The final report of the 1996 UN population projections will be published in late 1997.

We have, of course, also considered using the projections from the IIASA population program (Lutz 1996) or those of the US Bureau of the Census (1996*a*). However, the IIASA population scenarios are only available for 13 very large world regions, which are ecologically much too diverse for studying linkages between population and land or water resources. The projections of the US Bureau of the Census, on the other hand, are available for specific countries, but cover only the period from 1950 to 2020. This time-frame is certainly adequate from a chemographic point of view, but is rather short for investigating resource constraints. Also, the projections do not include any indication about the range of uncertainty, such as a lower and higher variant or a probability range. Only the UN population assessments and projections are available for all countries worldwide, include a higher and lower variant, and provide data series ranging from 1950 to 2050 which are long enough for biophysical research. Moreover, only the UN projections, which are now published every second year, have a history of more than four decades, which makes it possible to assess their predictive accuracy. The World Bank, which formerly published its own projections (Vu 1985), has cancelled this activity and uses the UN data.

2. MAJOR DEMOGRAPHIC TRENDS

(*a*) *World population will grow significantly in spite of falling fertility*

There is one most striking paradox in global population trends: on the one hand we have a rapid *decline* in fertility for more than two decades in many

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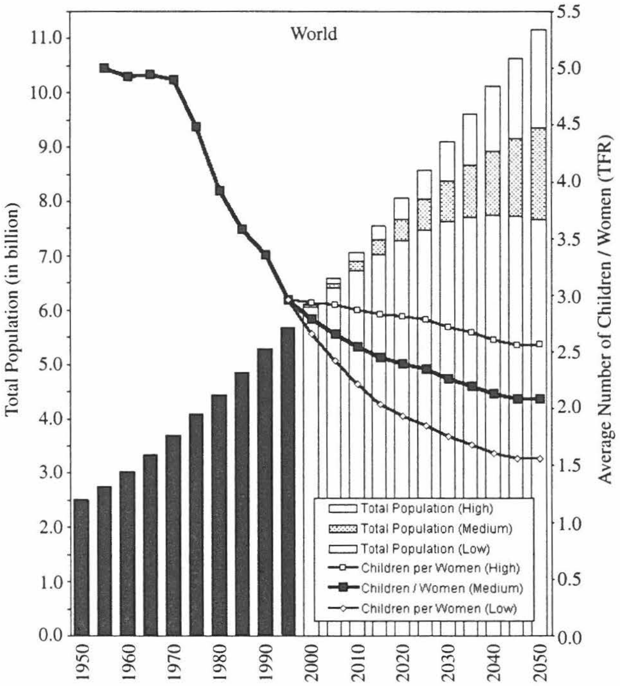

Figure 1. Total world population 1950–2050 (in billions) and average number of children per women (total fertility rate: TFR). High, medium and low variant UN projections 1996. (Source: UN Population Division.)

developing countries, to say nothing about the already extremely low fertility in most highly developed nations; on the other hand, we recently had the largest annual increase of world population in history. Each year between 1990 and 1995 some 85 million people were added to the world's population. Why is this the case and what are the recent estimates of fertility and population growth?

According to the most recent UN assessment, fertility—measured as a global *average*—began to decline in the mid-1970s. The world's population, however, will almost certainly continue to grow for several decades to come (see figure 1). According to the UN medium variant projection we will most likely have a global population of about 9.4 billion by 2050. This is somewhat lower than the Population Division's previous estimate of 9.8 billion in the 1994 edition of the *World Population Estimates and Projections.*

Even if one assumes an extremely rapid worldwide decline in fertility to an average of 1.6 children per woman—which most demographers would consider highly unlikely—we would see a further *increase* in the world's population up to about 7.7 billion people by 2050 (UN low fertility variant). However, it is not impossible that the global population might increase to more than 11 billion by 2050. Please note that this 'high' UN variant still assumes a worldwide fertility *decline* from currently 2.9 to about 2.6 children per woman (see figure 1 and table 1).

(*b*) *The current annual population increase of 80 million will probably remain constant until 2015*

Currently, the world's population is growing by about 80 million people per year (see figure 2). This is a little less than in the early 1990s, when the growth was more than 85 million per year. According to the most recent UN medium variant projection this will not change much during the next decades. Only after 2015 will we observe a gradual decline. By 2050—according to the UN medium variant—this annual increase in the world's population will be down to 'only' some 50 million. Thus, by the middle of the next century, world population growth (in absolute numbers) will have declined to the level of the early 1950s. However, this is only possible if fertility worldwide falls to the so-called 'reproductive level' of 2.1 children per woman by 2050. For countries like India, Pakistan or Nigeria, that is a long way to go.

It cannot be excluded that some populous countries will not reach this low fertility level by 2050. If, on average, worldwide fertility declines to only 2.6 children per woman, world population growth would further *increase.* Between 2020 and 2050 we would have a global *annual* population increase of about 100 million (see high variant UN projection in figure 2).

In the near future, the current world population increase could only decline if worldwide average fertility falls to 1.6(!) children per woman. There are not many demographers who would consider this level of fertility very likely. But only with such an extreme

Table 1. *Total population by region in 1950, 1995, 2025 and 2050 (in thousands): low, medium and high variant UN projections 1996; source: UN Population Division (1997)*

			UN projections, 1996					
	historical estimates		low variant		medium variant		high variant	
	1950	1995	2025	2050	2025	2050	2025	2050
world total	2523878	5687113	7474059	7662248	8039130	9366724	8580509	11156318
more developed regions	812687	1171384	1149984	959159	1220250	1161741	1286133	1351681
less developed regions	1711191	4515729	6324075	6703089	6818880	8204983	7294375	9804637
Africa	223974	719495	1370579	1731421	1453899	2046401	1546302	2408106
Eastern Africa	65624	221315	453249	593984	480182	698596	506719	812974
Middle Africa	26316	83271	181841	252289	187525	284821	200438	336396
Northern Africa	53302	158077	236621	258834	256716	317267	276175	381781
Southern Africa	15581	47335	78449	90256	82901	106824	87335	124900
Western Africa	63151	209498	420419	536058	446574	638892	475634	752055
Latin America and Caribbean	166337	476637	631598	649866	689618	810433	752670	1000555
Caribbean	17039	35686	44778	45478	48211	56229	51224	65827
Central America	36925	123474	175438	189415	189143	230425	206032	282729
South America	112372	317477	411382	414973	452265	523778	495414	651999
North America	171617	296645	336398	301140	369016	384054	393598	451503
Asia	1402021	3437787	4428376	4405219	4784833	5442567	5108307	6500750
Eastern Asia	671156	1421314	1572978	1374217	1695469	1722380	1785553	1999209
South-Eastern Asia	182035	481920	634064	651846	691911	811891	749613	994046
South-Central Asia	498583	1366866	1944779	2057954	2100034	2521304	2256712	3053930
Western Asia	50247	167686	276556	321202	297420	386992	316429	453566
Europe	547318	728244	669468	537521	701077	637585	736585	742331
Eastern Europe	219296	310506	271948	215673	284170	255955	303706	311048
Northern Europe	78094	93372	89039	75785	95593	94194	98776	105667
Southern Europe	109012	143377	131939	102990	137196	119887	142603	135502
Western Europe	140916	180988	176542	143072	184118	167550	191500	190115
Oceania	12612	28305	37640	37081	40687	45684	43047	53073
Australia/New Zealand	10127	21427	26380	24235	28809	30557	30561	35495
Melanesia	2095	5814	9636	11040	10150	12972	10655	15036
Micronesia	153	481	811	928	857	1097	905	1285
Polynesia	237	583	813	879	871	1059	926	1257
least developed countries	197572	579035	1092685	1384413	1159255	1631820	1231329	1916482

drop in fertility could we observe a shrinking of the world's population after 2040—assuming that there will be no disaster with a massive increase of mortality.

(c) *Between now and 2050 world population growth will be generated exclusively in developing countries*

Between now and the year 2050, the world's population will most likely increase by some 3.7 billion people: almost *all* will be contributed by the developing countries (see table 2). In fact, the population of the developed nations as a group will most likely decline by almost 59 million people between 2025 and 2050. Comparing the centennial growth of developed and developing countries reveals a dramatic divergence: the developed countries, as a group, will have increased their population by less than 350 million between 1950 and 2050. The developing countries, on the other hand, will have added almost 6.5 *billion* people—thus almost quintupling their 1950 population.

This modern 'population explosion' in the Third World is of course not comparable with anything we have experienced in the demographic transition of Europe during the 18th and 19th centuries. It is a historically *unique* phenomenon. Both the absolute numbers of population increase and the growth rates are without historical precedence. No country in Europe has experienced annual population growth rates of more than 0.5–1% during its 'high growth' period.

(d) *World population increase is concentrated in Asia*

From the almost 3.7 billion people that will be added to the world's population between now and 2050, Asia will contribute two billion (see table 2). This enormous population increase of 2000 million people is due to the already massive size of the population. Most of this growth will happen in the next three decades. Between 1995 and 2025, Asia's population will grow by 1.35 billion. Between 2025 and 2050, the increase will be only 658 million (see table 2).

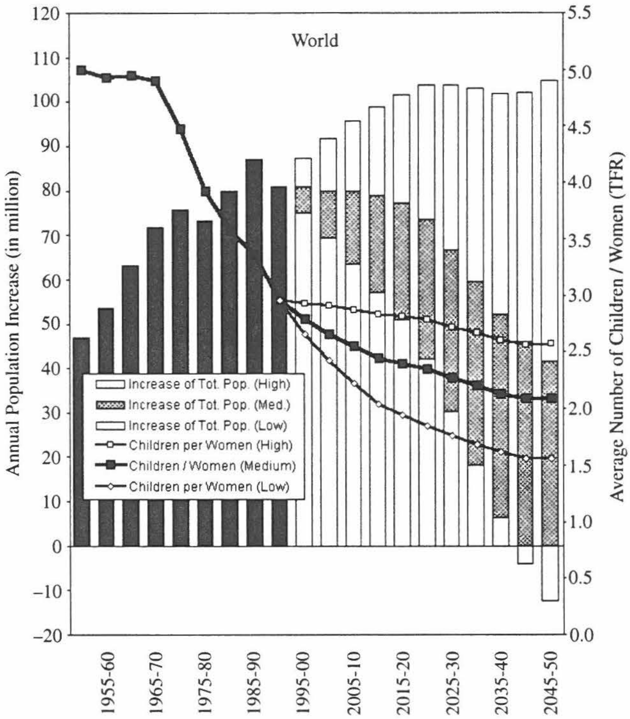

Figure 2. Average *annual* world population increase (in millions) and average number of children per women (total fertility rate: TFR). High, medium and low variant UN projections. (Source: UN Population Division 1997.)

During the next three decades Africa will contribute another 734 million people to the world's population, some 15 million more than its current total population. Despite a projected increase in mortality due to AIDS, we will not observe a significant slowing down of population growth in Africa—to say nothing of a decline. Fertility is still so high in sub-Saharan Africa that it can offset the effect of rising (infant and adult) mortality. Latin America and the Caribbean, on the other hand, will have only a moderate population increase of some 213 million between 1995 and 2025. This is due to both the smaller initial size of the population and the significant decline of fertility. Europe's population will almost certainly decline. The UN medium variant projection assumes a shrinkage of as much as 27 million during the next three decades.

(*e*) *By far the highest population growth rates can be found in Africa*

While Asia will contribute the largest number of people to modern world population growth, Africa will set the record in growth rates. In table 2 we have calculated the *annual* growth rates for various periods for all the major regions of the world (we have used true exponential growth rates, so that periods of various lengths can be compared).

Between now and the year 2025, Africa's population is projected to have an exponential annual growth rate of 0.44 %, while the populations of Latin America and the Caribbean will grow by 0.23 %, Asia by 0.21 %, and Northern America by 0.14 %. Europe's population, most likely, will decline by 0.02 %.

Please note that these projected growth rates for the next 30 years are actually lower than the historical growth rates during the past 45 years. Between 1950 and 1995, exponential annual growth rates were 0.49 (Africa), 0.44 (Latin America and the Caribbean), 0.38 (Asia) and 0.23 (Northern America). Even Europe had a positive growth rate of 0.12 (see table 2). In other words, in the past 45 years the population of Latin America grew twice as fast as it will grow in the next 30 years. We can also see that between 2025 and 2050 the United Nations Population Division assumes much slower population growth than during the next 30 years. While Africa, for instance, is projected to have a growth rate of 0.44 between 1995 and 2025, it should be only 0.26 between 2025 and 2050.

From a methodological point of view these growth rates for the *second* quarter of the next century are, of course, highly uncertain. But they show the critical phase of world population growth to be during the next three decades. If the world's population will increase to only 9.3 billion people, then most of this growth will happen during the next 30 years. If the growth rates are not down significantly by 2025, we will have a much larger population in 2050.

Table 2. *Population increase (in thousands) and in exponential annual growth rate (in %) by region during the periods 1950–1995, 1995–2025, 2025–2050 and 1950–2050: UN medium variant projection 1996; source: UN Population Division (1997)*

	population change and annual exponential growth rates							
	1950–1995		1995–2025		2025–2050		1950–2050	
	in 1000s	%	in 1000s	%	in 1000s	%	in 1000s	%
world total	3163235	0.34	2352017	0.22	1327594	0.12	6842846	0.25
more developed regions	358697	0.15	48866	0.03	−58509	−0.04	349054	0.07
less developed regions	2804538	0.41	2303151	0.26	1386103	0.14	6493792	0.30
Africa	495521	0.49	734404	0.44	592502	0.26	1822427	0.42
Eastern Africa	155691	0.51	258867	0.49	218414	0.28	632972	0.45
Middle Africa	56955	0.48	104254	0.51	97296	0.32	258505	0.45
Northern Africa	104775	0.46	98639	0.30	60551	0.16	263965	0.34
Southern Africa	31754	0.47	35566	0.35	23923	0.19	91243	0.36
Western Africa	146347	0.50	237076	0.48	192318	0.27	575741	0.44
Latin America and Caribbean	310300	0.44	212981	0.23	120815	0.12	644096	0.30
Caribbean	18647	0.31	12525	0.19	8018	0.12	39190	0.23
Central America	86549	0.59	65669	0.27	41282	0.15	193500	0.35
South America	205105	0.44	134788	0.22	71513	0.11	411406	0.29
North America	125028	0.23	72371	0.14	15038	0.03	212437	0.15
Asia	2035766	0.38	1347046	0.21	657734	0.10	4040546	0.26
Eastern Asia	750158	0.31	274155	0.11	26911	0.01	1051224	0.18
South-Eastern Asia	299885	0.41	209991	0.23	119980	0.12	629856	0.28
South-Central Asia	868283	0.42	733168	0.27	421270	0.14	2022721	0.31
Western Asia	117439	0.51	129734	0.36	89572	0.20	336745	0.39
Europe	180926	0.12	−27167	−0.02	−63492	−0.07	90267	0.03
Eastern Europe	91210	0.15	−26336	−0.06	−28215	−0.08	36659	0.03
Northern Europe	15278	0.07	2221	0.01	−1399	−0.01	16100	0.04
Southern Europe	34365	0.11	−6181	−0.03	−17309	−0.10	10875	0.02
Western Europe	40072	0.10	3130	0.01	−16568	−0.07	26634	0.03
Oceania	15693	0.34	12382	0.23	4997	0.09	33072	0.03
Australia/New Zealand	11300	0.31	7382	0.19	1748	0.04	20430	0.21
Melanesia	3719	0.43	4336	0.35	2822	0.19	10877	0.34
Micronesia	328	0.48	376	0.36	240	0.19	944	0.37
Polynesia	346	0.38	288	0.25	188	0.15	822	0.28
least developed countries	381463	0.45	580220	0.44	472565	0.26	1434248	0.40

Table 3. *The ten countries with the highest population increases during 1950–1995, 1995–2025, 2025–2050 and 1950–2050: UN medium variant projection 1996; source: UN Population Division (1997)*

(The dashes indicate countries which were not among the ten with highest population growth in a particular period.)

country	past population increase 1950–1995 (in 1000s)	projected population increase 1995–2025 (in 1000s)	projected population increase 2025–2050 (in 1000s)	centennial population increase 1950–2050 (in 1000s)
China	665464	260206	40372	961904
India	571444	401196	173982	1175113
Indonesia	117922	77785	36802	238726
USA	109302	65366	—	189730
Brazil	105040	—	23143	189284
Pakistan	96744	132647	72642	317840
Nigeria	78786	126676	80945	305575
Bangladesh	76446	61751	32585	176405
Mexico	63408	—	—	—
Iran (Islamic Republic of)	51452	59886	34993	153356
Ethiopia	—	79884	62534	194298
Zaire	—	60472	47987	—

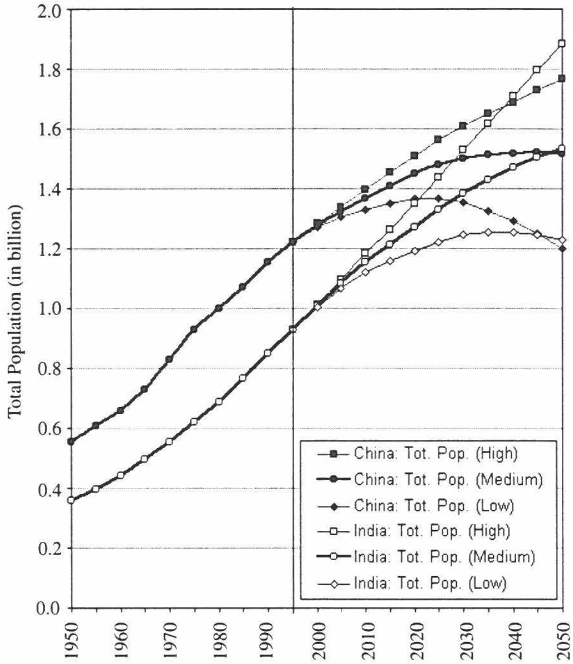

Figure 3. China and India: total population 1950–2050 (in billions). Low, medium and high variant UN projections 1996. (Source: UN Population Division 1997.)

(*f*) *Ten countries will contribute most to world population growth during the next 30 years*

The ten countries which will contribute most to world population growth over the next 30 years are India, China, Pakistan, Nigeria, Ethiopia, Indonesia, the United States of America, Bangladesh, Zaire and Iran—in that order!

According to the most recent UN population projection, India will add more than 400 million to its population between 1995 and 2025. China will grow by only 260 million (see table 3). The next largest contributor to world population growth, surprisingly, is not Indonesia, which has the third largest population among developing countries, but Pakistan. Pakistan will grow by about 133 million between 1995 and 2025. An almost equal contribution to world population growth will probably come from Nigeria—127 million. Perhaps unexpected, the next largest contributor to world population growth will be Ethiopia, which will add another 80 million people. Indonesia, on the other hand, will grow by 'only' 78 million—which is only ranked six in the 'hit list' of contributors to world population growth. The United States will probably grow by 65 million and Bangladesh by 62 million. Few development experts would have put Zaire on a watch list for population problems. But the population in this Central African country is projected to grow by more than 60 million. The tenth largest contributor to world population growth will be Iran—with a population increase of almost 60 million between 1995 and 2025 (see table 3).

(*g*) *India will out-grow China*

India has one of the oldest family planning programmes. It started way back in the 1950s. The country's average fertility, however, declined only slowly. In the early 1950s, both China and India had a total fertility rate (TFR) of about six children per woman. But while China's TFR sharply fell to about 2.4 in 1990, it declined only slowly in India and was still above four children per woman in 1990. This relatively slow decline of fertility has built up a huge population momentum in India. The country's population structure is much 'younger' than that of China. These young adults—born during the high growth period in the 1950s, 1960s and even 1970s–will have children in the near future. Even if fertility continues to decline to reproductive level by 2020 (as being assumed by the UN projections), the Indian population will probably increase to almost 1.6 billion by 2050, slightly more than that of China (UN medium variant) (see figure 3). However, India's population might become even larger. If the average TFR would only decline to 2.6 (instead of 2.1) children per woman in 2020, the population would increase to about 1.9 billion(!) by 2050 (see high UN variant in figure 3).

(*h*) *Nigeria and Pakistan: emerging population giants*

There are not many countries in the world where population projections are more difficult to believe than in Nigeria. If the latest UN projections are

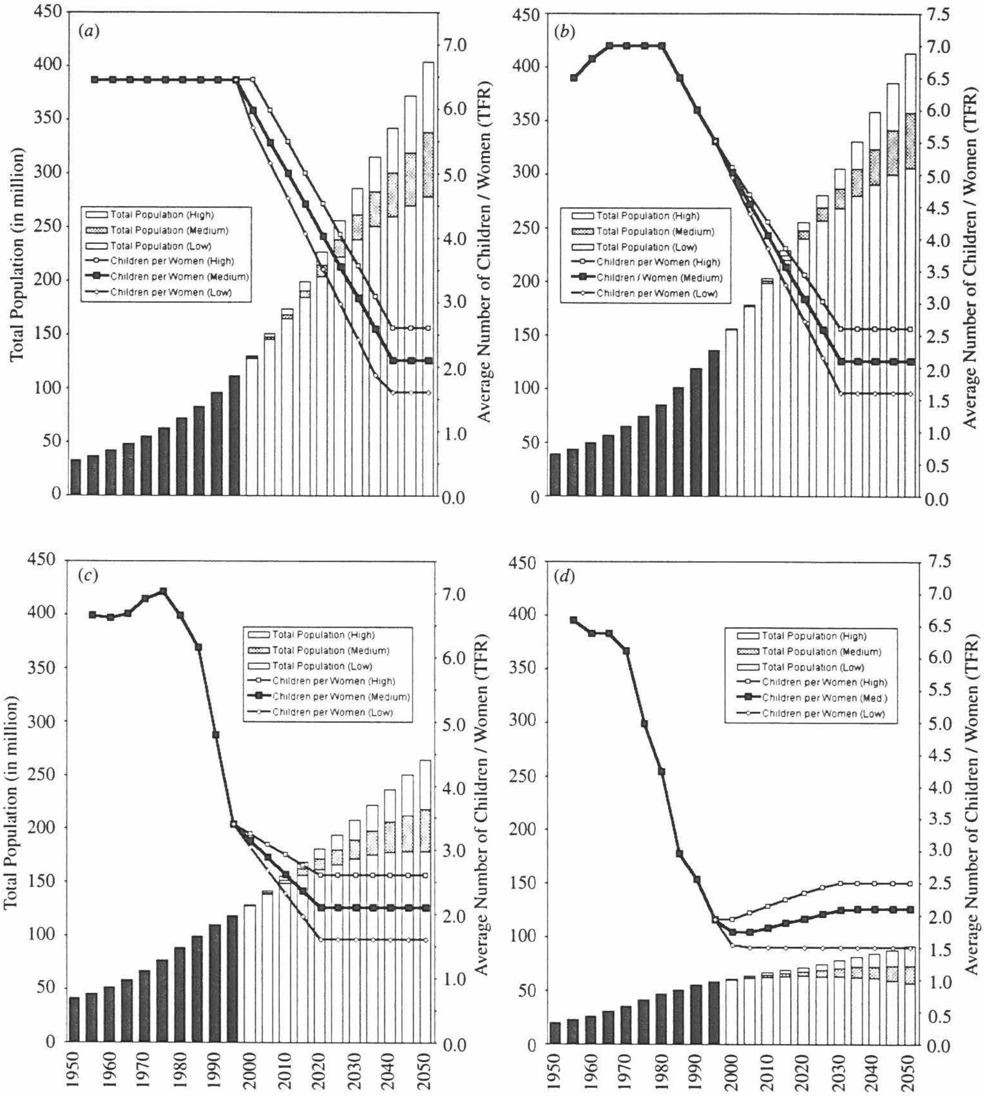

Figure 4. Total populations 1950–2050 (in millions) and average number of children per woman (total fertility rate: TFR) in (*a*) Nigeria, (*b*) Pakistan, (*c*) Bangladesh and (*d*) Thailand. (All charts are to the same scales. Source: UN Population Division 1997.)

correct, then our children (and the younger among us) will watch the emergence of an African population giant, comparable to the most populous Asian nations. In 1950, the West African countries had a population of about 33 million; since then, the population has more than tripled. The UN Population Division estimates that Nigeria's population in 1995 was about 112 million (note that the UN does *not* revise their estimate according to the most recent Nigerian census, which was significantly lower. Obviously, the UN Population Division do not consider this census accurate enough). Between now and the year 2050, the country's population will probably triple again and reach almost 339 million (see figure 4). If that really happens, we will have a ten-fold increase of a 33 million population within one century. This would have no historical precedence. Note that we are talking about the *medium* variant UN projection. Based on the demographic parameters it would be not impossible if Nigeria's population would grow even faster.

There are other overwhelmingly Muslim populations with very high population growth rates, such as those of Saudi Arabia, Kuwait or the United Arab Emirates. But none of them is projected to have such a massive absolute increase in population as Pakistan. In 1950, Pakistan had a population of about 40 million people, and was quite comparable in population size to Bangladesh (42 million), Brazil (54 million) or Italy

Table 4. *Total population (in thousands) and proportion of global population by region (in %), 1950, 1995, 2025 and 2050: UN medium variant projection 1996; source: UN Population Division (1997)*

	total population (in 1000s)				percentage of world population			
	1950	1995	2025	2050	1950	1995	2025	2050
world total	2523878	5687113	8039130	9366724	100.0	100.0	100.0	100.0
more developed regions	812687	1171384	1220250	1161741	32.2	20.6	15.2	12.4
less developed regions	1711191	4515729	6818880	8204983	67.8	79.4	84.8	87.6
Africa	223974	719495	1453899	2046401	8.9	12.7	18.1	21.8
Eastern Africa	65624	221315	480182	698596	2.6	3.9	6.0	7.5
Middle Africa	26316	83271	187525	284821	1.0	1.5	2.3	3.0
Northern Africa	53302	158077	256716	317267	2.1	2.8	3.2	3.4
Southern Africa	15581	47335	82901	106824	0.6	0.8	1.0	1.1
Western Africa	63151	209498	446574	638892	2.5	3.7	5.6	6.8
Latin America and Caribbean	166337	476637	689618	810433	6.6	8.4	8.6	8.7
Caribbean	17039	35686	48211	56229	0.7	0.6	0.6	0.6
Central America	36925	123474	189143	230425	1.5	2.2	2.4	2.5
South America	112372	317477	452265	523778	4.5	5.6	5.6	5.6
North America	171617	296645	369016	384054	6.8	5.2	4.6	4.1
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Eastern Asia	671156	1421314	1695469	1722380	26.6	25.0	21.1	18.4
South-Eastern Asia	182035	481920	691911	811891	7.2	8.5	8.6	8.7
South-Central Asia	498583	1366866	2100034	2521304	19.8	24.0	26.1	26.9
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Northern Europe	78094	93372	95593	94194	3.1	1.6	1.2	1.0
Southern Europe	109012	143377	137196	119887	4.3	2.5	1.7	1.3
Western Europe	140916	180988	184118	167550	5.6	3.2	2.3	1.8
Oceania	12612	28305	40687	45684	0.5	0.5	0.5	0.5
Australia/New Zealand	10127	21427	28809	30557	0.4	0.4	0.4	0.3
Melanesia	2095	5814	10150	12972	0.1	0.1	0.1	0.1
Micronesia	153	481	857	1097	0.0	0.0	0.0	0.0
Polynesia	237	583	871	1059	0.0	0.0	0.0	0.0
least developed countries	197572	579035	1159255	1631820	7.8	10.2	14.4	17.4

(39 million). Since then Pakistan's population has more than tripled, and stood at 136 million in 1995. At that time the populations of Brazil, Bangladesh and Italy were 159, 118, and 57 million, respectively. But the real population explosion in Pakistan will come during the next few decades. The population not only has a very large proportion of young men and women of reproductive age, but also still extremely high fertility—much higher, for instance, than in Bangladesh or Brazil. These young couples will produce a large number of children even if we assume, as in the UN medium variant, a decline of average fertility to reproductive level (of 2.1 children per woman) by 2020. Pakistan's population will be about 357 million by 2050 (according to the UN medium variant projection)—far larger than that of Bangladesh (218 million), Brazil (243 million) or Italy (42 million) (see figure 4). However, it is (demographically) not impossible that Pakistan's population will increase even further to some 413 million by 2050 (UN high variant projection).

High fertility in the early 1950 was not the only reason for the exceptional population growths of Nigeria and Pakistan. There were other countries which had a similar or even higher level of fertility. Consider the case of Bangladesh and Thailand. The TFR in Bangladesh during the early 1970s was as high as that of Nigeria or Pakistan, and the initial population size was quite comparable. Yet Bangladesh is projected to have a population of 'only' 220 million by 2050 (as compared to Nigeria's 339 million). Thailand is one of the Asian 'success stories' in population control: its average TFR was as high as in Nigeria but has declined sharply since the 1970s. As a result Thailand will have a very moderate population increase between now and 2050 of only some 14.7 million (see figure 4).

(i) *The global balance of the world's population has shifted significantly between 1950 and 1995. It will change even more dramatically between now and 2050*

Europe's share of the world's population has declined sharply from 21.7 % in 1950 to 12.8 % in 1995. Africa's share, on the other hand, has increased from 8.9 to 12.7 % (see table 4). Today, both Europe and Africa are each home to about one-eighth of the world's population. This will change significantly in the future. Europe's share of the global population will shrink to about 6.8 % in 2050. Africa's share will grow to 21.8 %. Hence, one century of population growth will completely reverse Europe's and Africa's position: Europe's share of the global population in 2050 will be the same as that of Africa in 1950. If the UN medium variant projections turn out to be correct (and there is no sign that they may be utterly wrong) we have to expect a dramatic change in the global balance of the population: a much bigger share of the world population will live in Africa, south of the Sahara. In only some 50 years, Western Africa, for instance, will have the same population as *all* of Europe and Eastern Africa will have much more people than all the countries of South America, the Caribbean and Oceania *combined.*

(*j*) *Worldwide, the population will age*

During the next decades the world population structure will inevitably age. This is an unavoidable consequence of large birth cohorts during the 1950s and 1960s and the rapid fertility decline since the 1970s. In 2025 the 'baby boomers' of the 1950s and 1960s will be between 65 and 75 years of age. These large aging cohorts are followed by the relatively small 'baby bust' generations of the worldwide fertility decline.

In 1950, there were only 131 million people of age 65 and older; in 1995 the number of elderly had tripled—it was estimated at 371 million. Between now and the year 2025 it will more than double again, and by 2050 we might have more than 1.4 billion elderly worldwide (see table 5). In 1950, only 5.2 % of the world's population were aged 65 or more; today the percentage has already increased to 6.2 %, and by 2025 one out of ten people worldwide will be 65 years of age or more.

While currently population aging is most serious in Europe and Japan, Eastern Asia (China) will experience a dramatic increase in the proportion of elderly people by the middle of the next century. This is largely due to the country's success in family planning, which rapidly reduced the relative size of birth cohorts since the 1970s.

2. THE DEMOGRAPHIC MOMENTUM

As we have demonstrated with the projections above there is almost no doubt that the world population will grow for quite some time. Of course we can imagine massive natural catastrophes, such as the world being hit by a huge meteor; we can also think about the emergence of a highly contagious lethal virus for which no cure or immunization can be found; or we could be frightened about a worldwide nuclear war that might result in sudden, non-reversible climate change—but short of these highly unlikely events, almost nothing could stop the global population from increasing by another few billion people. Why are we so sure about this?

First, there is a driving force concealed in the 'young' age structure of the world's population that just cannot be switched off. Due to high fertility in the 1950s, 1960s and early 1970s in many developing countries, large numbers of women (and men) are currently entering reproductive age. The world is full of young adults that will have children. Even if each couple has a smaller number of children than their parents, the total number of offspring will be substantial. This 'echo effect' of a high-fertility period in the past creates a 'demographic momentum' which works against changes in reproductive behaviour that favour smaller families. Second, it is highly unlikely that large populations will *instantly* change their reproductive behaviour. Certain sections of a population, such as highly educated middle-class couples in urban areas, might adopt radical behavioural change almost overnight, but many developing countries still have large rural populations where fertility is linked to deep-rooted cultural values or social conditions, and can decline only gradually over two or three generations. We must also take into account that the average fertility of a population is a composite measure which results from the reproductive behaviour of several parent cohorts: these include couples which already have a certain number of children and can only reduce the number of additional offspring. Even in a country like China, where we have a highly controlled society and a most rigorous family planning programme, it took 20 years to reduce average fertility from about 6 to 2.4 children. In India, according to UN projections, this process might take 60 years or more.

These two basic facts, which are well known among demographers, tend to slow down demographic change. They can produce a considerable time-lag between the first signs of a fertility decline and a slow down in population growth. In fact, it is quite typical for developing countries that the total number of births increases for one or even two decades, while the fertility (that is the average number of children per woman) already declines. Consider figure 2 in which we have plotted global population growth together with the change in TFR as being derived from the 1996 round of UN population assessments and projections. Note that between 1950 and 1995, the chart is based on (estimates of) historical data, while from 1995 to 2050, both the total population and the TFR are projected. Globally, the TFR dropped from about five children per woman in 1950 to some 2.9 in 1995; during that same period, the world's population more than doubled from 2.5 to 5.2 billion. The UN assumes a further steep decline in fertility to 2.1 children in 2050. During that period the world population will further increase to 9.3 billion people.

Between 1965 and 1995, while the TFR dropped significantly, the annual increase in the world's population grew from about 65 to 85 million. In other words, more and more people were added to the global population, while couples had less and less children (see figure 2).

These contrary trends become even more apparent when we plot *indices* of the TFR, the average annual increase in the population and the annual population growth rates. For the five-year period of 1950–1955, the indices are set to 100 (see figure 2). This 'paradox' is simply a consequence of the fact that the increase in the number of parents outpaced the decline in fertility. In fact, this situation will continue for some time. According to the most recent UN projections we will have a stable annual increase of about 80 million people until 2015—only then will this increase gradually decline to about 47 million in 2050. By the middle of the next century the world's population will still grow by about the same number of people as there were in 1950—only the total number of people on the planet will be more than three times larger.

3. WHAT DO WE *NOT* KNOW ABOUT FUTURE POPULATION GROWTH?

We know that fertility is declining almost everywhere. But we do *not* know how *fast* and to what level it will fall. There is not much indication that some Islamic countries, such as Pakistan or the Gulf states in Western Asia, will have significantly lower fertility in the near future. On the other hand there are signs that fertility is dropping even faster than expected in several other Asian and even African countries. This would result in a smaller world population than previously expected. Some researchers even believe that the global population could stabilize somewhat below 10 billion people in the long run (Lutz 1996). Of course, this is to a large extent based on educated speculation, since it depends on assumptions about changes in reproductive behaviour of people who are not even born today. There is great controversy among demographers as to whether these assumptions can be justified: some highly respected demographers, such as Nathan Keyfitz or Joel E. Cohen, have argued that population projections are impossible beyond 10 or 15 years (Keyfitz 1981; Cohen, 1995). Others have applied sophisticated methodologies, such as probabilistic projections, to calculate even very long-term projections (or scenarios) up to the year 2100 (Lutz 1996). Those who have regularly conducted world population projections for more than three decades, such as the UN Population Division, can argue that their projections were fairly accurate if compared with the actual development (see Heilig 1996).

The debate is still undecided. The only thing we know for sure is that there is *a high degree of uncertainty* for any projection that expands over more than two or three decades. One reason for this uncertainty is the high sensitivity of long-term projections to different

Table 5. *Total number (in thousands) and proportion of elderly (in %) of total population by region in 1950, 1995, 2025 and 2050: UN medium variant projection 1996; source: UN Population Division (1997)*

	population age 65+ (in 1000s)				population age 65+ as % of total population			
	1950	1995	2025	2050	1950	1995	2025	2050
world total	130669	370707	801929	1415924	5.2	6.5	10.0	15.1
more developed regions	64052	157950	246503	287373	7.9	13.5	20.2	24.7
less developed regions	66617	212757	555427	1128551	3.9	4.7	8.1	13.8
Africa	7058	22702	61211	161408	3.2	3.2	4.2	7.9
Eastern Africa	1915	6121	15601	46282	2.9	2.8	3.2	6.6
Middle Africa	999	2606	6236	17220	3.8	3.1	3.3	6.0
Northern Africa	1844	6104	17749	42302	3.5	3.9	6.9	13.3
Southern Africa	565	2014	5299	12112	3.6	4.3	6.4	11.3
Western Africa	1736	5856	16326	43491	2.7	2.8	3.7	6.8
Latin America and Caribbean	6220	24171	66425	135362	3.7	5.1	9.6	16.7
Caribbean	760	2376	5214	9233	4.5	6.7	10.8	16.4
Central America	1498	5123	15815	36968	4.1	4.1	8.4	16.0
South America	3963	16671	45395	89161	3.5	5.3	10.0	17.0
North America	14102	37080	68367	82550	8.2	12.5	18.5	21.5
Asia	57384	183427	458581	863449	4.1	5.3	9.6	15.9
Eastern Asia	29978	96559	225266	345838	4.5	6.8	13.3	20.1
South-Eastern Asia	6774	20712	56393	124734	3.7	4.3	8.2	15.4
South-Central Asia	18428	58757	155694	345205	3.7	4.3	7.4	13.7
Western Asia	2204	7399	21229	47671	4.4	4.4	7.1	12.3
Europe	44981	100620	141764	164798	8.2	13.8	20.2	25.8
Eastern Europe	14287	38201	50967	59786	6.5	12.3	17.9	23.4
Northern Europe	8045	14343	19323	21645	10.3	15.4	20.2	23.0
Southern Europe	8303	20913	30810	37085	7.6	14.6	22.5	30.9
Western Europe	14347	27163	40665	46282	10.2	15.0	22.1	27.6
Oceania	930	2724	5601	8384	7.4	9.6	13.8	18.4
Australia/New Zealand	839	2504	4948	6717	8.3	11.7	17.2	22.0
Melanesia	82	182	532	1375	3.9	3.1	5.2	10.6
Micronesia	3	15	52	126	2.0	3.1	6.1	11.5
Polynesia	6	24	70	165	2.5	4.1	8.0	15.6
least developed countries	6521	17658	45543	124915	3.3	3.0	3.9	7.7

assumptions on the *timing* of the fertility decline. Even if all demographers would agree that fertility will come down to 2.1 children per woman in 2050 (which is the current UN assumption) a few years delay in this decline can make a difference for a world population of a few *billion* people.

So far we have only talked about fertility. Of course this is a crude simplification. The real trouble begins when we take into account future changes in mortality. It was conventional wisdom among demographers for quite some time that mortality is not a very important issue when it comes to population projections: the developing countries would simply follow the trends in the developed world which were thought to have already stabilized. The lowest level of infant mortality would be around ten deaths per 1000 life births, and the *maximum* life expectancy would be about 82.5 years for men and 87.5 years for women (this was the UN assumption since their 1988 round of projections). However, things have changed unexpectedly. First, there is an ongoing decline in mortality in many developed countries. In particular, adult and old-age mortality is falling quite significantly for both men and women. *Average* life expectancy in some of these populations (such as in Austria) has increased by about two years per decade during the 1970s, 1980s, and 1990s. A growing number of people are approaching ages that were previously considered a biological upper limit of the human life span. Microbiological and genetic research has made a big step forward to understand (and possibly manipulate) the process of aging. It is not impossible that human life can be significantly expanded in the future by a combination of dietary practices, specific drugs and genetic therapy. Second, the expected across-the-board decline of mortality in the developing world has not materialized. While some developing countries, such as China, have seen a spectacular increase in life expectancy, others have lagged behind or, in fact, have even experienced recent declines. Previous assumptions might have been overoptimistic, especially for sub-Saharan Africa, given the high prevalence of HIV-infection and AIDS, newly spreading tropical diseases and widespread violent conflicts.

Both trends have added *uncertainty* to our population projections, or rather made us aware of the uncertainty that was already there. While the prospects for increasing longevity among highly developed populations might only amplify their structural problems of aging, it is the new threat from AIDS and other causes in developing countries which could have a significant impact on world population growth. So far this is not in sight, but no one knows the future of the AIDS epidemic in India or other populous Asian countries. There is indication, for instance, that HIV infection is spreading rapidly in India and Thailand (US Bureau of the Census 1996*b*).

The best strategy for reducing this uncertainty in population projections is to regularly revise the estimates, based on the most recent demographic evidence. The UN Population Division has an excellent record for continuously fine-adjusting of their estimates. Also, their early estimates from the 1960s seem to have been remarkably accurate for the year 2000 (see Heilig 1996).

4. ESTIMATING THE BALANCE OF REMAINING LAND WITH CULTIVATION POTENTIAL

In this section we discuss to what extent the availability of land resources in the less developed countries can be expected to support the unprecedented population growth that will occur over the next 2–3 decades in many regions. The aim is to estimate the amount of land that from climatic, edaphic and topographic conditions may be adjudged the capability to sustain food crop production. Furthermore, we are interested in the relative quality of these lands, their broad geographic distribution as well as the major type of ecosystems that presently cover these areas.

The UN Food and Agriculture Organization (FAO), together with IIASA, has developed and widely applied a methodological framework for assessments of land productivity which originally was designed for use in agricultural development planning and natural resources management (FAO 1978–81; FAO/IIASA 1993; Fischer & van Velthuizen 1996). A first assessment comparing crop production potential to minimum food requirements concluded that, overall, less developed regions would be able to feed their growing populations (FAO/IIASA/UNFPA 1982). Agroecological zoning (AEZ) involves the inventory, characterization, and classification of the land resources in a way that is meaningful for assessments of the potential of agricultural production systems. This characterization of land resources includes components of climate, soils and landform, basic for the supply of water, energy, nutrients and physical support to plants.

Crops require heat, light, and water in varying amounts. The geographic distribution of crops is mainly governed by these climatic elements. Temperature, water, and solar radiation are key climatic parameters which condition the net photosynthesis and allow crops to accumulate dry matter according to the rates and patterns which are specific to individual crop species. Crops have specific temperature requirements for their growth and development, and prevailing temperatures set the limits of crop performance when moisture (and radiation) requirements are met. Similarly, when temperature requirements are met, the growth of a crop is largely dependent on how well the length of its growth cycle matches the period when water is available. In the AEZ approach, this has led to the concept of the length of growing period (LGP) which is defined as the period (in days) during the year in which water availability and prevailing temperature can sustain crop growth.

Crop performance depends as well on the availability of nutrients in the soil, its capacity to store water and to provide mechanical support for crops. Therefore, agroecological zoning also includes an inventory of relevant soil and landform characteristics. The specific combinations of climatic, soil and terrain inventories form the basic land resources units of analysis.

Technical specifications (including management) within a socio-economic setting under which a specific crop is grown have been defined as land utilization types (LUT). Crop suitability assessments, in essence, are based on matching of crop specific adaptability characteristics and LUT ecological requirements with the attributes of individual land units.

(*a*) *Estimating the extent of land with crop production potential*

To estimate the scope for expanding agriculture in response to population growth in developing countries, and to assess the possible impact on forest ecosystems of increasing the extents of cultivated land, a rather detailed assessment of land resources and land with rainfed cultivation potential was carried out at IIASA to provide inputs to an FAO study (FAO 1995). Some of the calculation steps were recently repeated using additional data and procedures, involving five main steps: (i) quantifying land with cultivation potential; (ii) delineation of protected areas; (iii) subtracting land for habitation and infrastructure; (iv) overlaying of global ecosystems database; and (v) subtraction of land currently in cultivation.

The input for the evaluation of land with rainfed crop production potential consists of several geo-referenced data sets: (i) the inventory of soil and land form characteristics from the FAO–UNESCO Soil Map of the World (SMW) (FAO 1991); and (ii) the inventory of climate regimes in which data on temperature, rainfall, relative humidity, wind speed and global radiation are used together with information on evapotranspiration to characterize the thermal regimes and length of growing periods. The digitized inventories were overlaid to create a land resources inventory composed of several hundred thousands of land units, i.e. pieces of land of varying size with unique soil, land form and climate attributes.

Each land unit was tested for its suitability to grow any of the selected 21 major agricultural crops, under three levels of technology. (The crops are: millet, sorghum, maize, spring wheat, winter wheat, barley, bunded rice, upland rice, sweet potato, cassava, white potato, phaseolus bean, groundnut, soybean, cowpea, chickpea, oil palm, sugarcane, banana, olive and cotton.)

The estimated yields for each land unit, crop and technology alternative were then compared with those obtainable in the same major climate zone but without soil and terrain constraints, the latter yields being termed the maximum constraint-free yield. Any piece of land so tested, or part thereof, is classified as suitable for rainfed crop production if at least one of the crops could be grown under any one of the three technology alternatives, with a yield of 20% or more of the maximum constraint-free yield for that management level. If more than one crop met this criterion, the amount of land classified as suitable was determined on the basis of the crop which could use the largest part of the land unit. Land units where none of the 21 crops met this criterion were classified as not suitable (NS) for rainfed crop production.

The land assessed as having potential for rainfed crop production is further classified into three broad suitability classes. When simulated crop yields were within 80–100% of maximum constraint-free yield, the land was classified as very suitable (VS), suitable (S) when within 40–80%, and marginally suitable (MS) when assessed yield levels were 20–40%. In presenting the results we consider five aggregate land classes, based on the combination of moisture conditions and crop suitability, as used by the FAO (FAO 1988, 1995): (1) Low rainfall class (LOW): dry semi-arid areas with length of growing periods of 75–120 days, all suitable soils. (2) Uncertain rainfall class (UNC): moist semi-arid areas with LGP of 120–180 days and very suitable (VS) or suitable (S) land. (3) Good rainfall class (GOOD): subhumid areas with LGP of 180–270 days and very suitable (VS) or suitable (S) land. (4) Problem area class (PROB): includes VS, S and MS land in humid and per-humid regions (with LGP greater than 270 days), and moderately suitable (MS) land in LGPs of 120–270 days. (5) Naturally flooded class (NFL): includes all suitable land where soils are classified as Fluvisols or Gleysols.

(*b*) *Delineation of protected areas*

When land is indicated as legally-defined protected (national parks, conservation forest and wildlife reserves) the respective land units are evaluated for cultivation potential but not considered available for agricultural expansion. In the study, the relevant data were available for 63 of the developing countries. Maps and inventories of national parks, conservation forest and wildlife reserves (IUCN 1990) were made available by the World Conservation and Monitoring Centre (Cambridge, UK) and provided to IIASA by the FAO. The data on protected areas are geo-referenced and thus could be overlayed on the land resources inventory. These areas delineated in the GIS occupy a total of almost 400 million ha, i.e. about 6% of the total land area in developing countries (excluding China). Of this, around 200 million ha were assessed as having some potential for crop cultivation, representing about 8% of the total extent with crop cultivation potential.

(*c*) *Subtraction of land for habitation and infrastructure*

We have also attempted to broadly estimate the amount of land currently used for habitation and infrastructure occupying areas assessed as having cultivation potential. Detailed information to estimate region-specific land use for these purposes is scarce. The functional relationship parameterized in the study relies mainly on county-level data from China. It expresses per capita use of land for habitation and infrastructure in relation to population density. Examples of the parameterization are as follows: at 35 persons per km^2 the simulated requirement is 50 ha per 1000 people (i.e. 1.75% of the land); at 150 persons per km^2, the use is 26 ha per 1000 people (i.e. 3.9% of the land), at 675 persons per km^2 the use is 20 ha per

Table 6. *Balance of land with rainfed crop production potential in less developed regions: authors' calculation based on FAO (1995)*

	low rainfall area (LOW) 1000 ha	uncertain rainfall area (UNC) 1000 ha	good rainfall area (GOOD) 1000 ha	problem area (PROB) 1000 ha	gleysols and fluvisols (NFL) 1000 ha	total with rainfed cultivation potential 1000 ha	% of total
gross	161997	361849	645013	1232641	357708	2759207	100.0
protected	7526	19204	44691	100462	29334	201217	7.3
habitation 90	4038	10801	15275	23643	9672	63430	2.3
net	150433	331844	585046	1108537	318702	2494561	90.4
cultivated	87565	154757	267084	262694	90571	862671	31.3
balance	62868	177087	317962	845843	228131	1631890	59.1
% forest and wetland	34	45	58	71	75	65	—
forest and wetland	21493	79311	185409	599190	170552	1055956	64.7
other	41375	97775	132553	246652	57579	575933	35.3

1000 persons (some 13.5% of the land), etc. Based on a georeferenced data set of population density, the respective subtraction of land for habitation and infrastructure purposes is carried out in each land unit.

(*d*) *Overlaying of the global ecosystems database on the land with cultivation potential*

To estimate the distribution of ecosystems among land assessed as having rainfed crop production potential a global ecosystems digital database (Kineman & Ohrenschall 1992). was overlayed with the land resources data. The data set is coded on a 10′ by 10′ latitude/longitude raster of grid-cells, providing an adequate resolution for regional studies. Sixty ecosystem classes are distinguished in the data set which were aggregated into 12 aggregate land-cover categories, as shown in Appendix 1.

The GIS operation overlaying the results of the agroecological assessment with the global ecosystems database was tabulated by country to derive the distribution of ecosystems within land classes with cultivation potential. Tabulation of land resources, both by detailed and aggregate classes, has been carried out. For presentation here, the results were then further aggregated according to broader geographic regions.

(*e*) *Subtraction of land currently under cultivation*

The steps previously described resulted in geographically explicit accounts of land with cultivation potential characterized in terms of major ecosystems classes. Finally, to subtract from these the land areas currently under cultivation two main data sources were relied upon: a digital copy of the accounts of cultivated land compiled by the FAO (FAO 1995; Appendix 2), and the distribution of farmland ecosystem classes found in the global ecosystems database. It includes ten ecosystem classes of pure or mixed agricultural use, which were merged into three aggregated land-cover categories. We anticipate that activities currently underway by the International Geosphere-Biosphere Programme (IGBP) to develop high resolution global data sets on land cover and elevation (Townshend 1992) will help to improve the accuracy of our estimation.

Regional land balances of areas with cultivation potential obtained by applying the five-step procedure previously described are presented in Appendix 2, a summary for all less developed countries is shown in table 6 (for an explanation of table entries refer to table 6*b* in Appendix 2).

5. HOW WELL DO LAND AND WATER RESOURCES MATCH THE ANTICIPATED REGIONAL POPULATION MOMENTUM?

As a first check of the extent to which the balance of remaining land with cultivation potential would enable the various regions to cope with the demographic trends outlined in §§1–3, demand for arable land was estimated under crude assumptions for projected 2030 and 2050 population levels. In the simplest case it is assumed that (i) the additional demand for cultivated land increases linearly with population; and (ii) only a fraction, overall in the order of 20% but varying with region, of the additional agricultural output needed will have to be met from expanding cultivated land. In specifying this fraction, we have broadly adopted the assumptions of the FAO (FAO 1995) (see table 7). For instance, in sub-Saharan Africa about 30% of the contribution to total crop production increases is assumed to be derived from expansion of cultivated land. For land-scarce Asian regions, this is assumed to be only about 5%.

Table 8 summarizes the calculations using population levels projected for years 2030 and 2050 (UN, 1997). The share of production increases not accounted for by expanding cultivated land would have to come from intensification, i.e. higher yields, reduced fallow periods and a larger number of crops per year. Table 8 compares, for groups of countries in less developed regions, the additional need for cultivated land estimated under these assumptions to the balance of

Table 7. *Sources of growth in crop production and in harvested area, in developing countries, excluding China (%): source: FAO (1995)*

	crop production				harvested land	
	1970–90 contribution of increases in:		1988/90–2010 contribution of increases in:		1988/90–2010 contribution of increases in:	
	yields	harvested land	yields	harvested land	arable land	cropping intensity
developing countries	69	31	66	34	62	38
Africa (sub-Saharan)	53	47	53	47	64	36
Near East/North Africa	73	27	71	29	31	69
East Asia	59	41	61	39	82	18
South Asia	82	18	82	18	22	78
Latin America and Caribbean	52	48	53	47	60	40

Table 8. *A simple balance of cultivated land in 2050 (1000 ha): authors' calculation based on FAO (1995)*

region	cultivated land in 1990	total balance	share in forest and wetlands	balance excluding forest and wetlands	% of production increase from land	additional cultivated land required in 2050
Central America and Caribbean	36920	51966	0.80	10289	20	14603
South America	152965	710775	0.69	221762	30	82107
Latin America	189885	762740	0.70	232051	28	96710
Eastern Africa	62860	185435	0.70	58558	30	68015
Middle Africa	43137	338398	0.75	86292	30	52478
Northern Africa	40409	67093	0.26	49380	15	13513
Southern Africa	15849	28062	0.23	21636	30	12031
Western Africa	90328	103057	0.36	65854	30	95666
Africa	252583	722046	0.61	279719	29	241703
Western Asia	36831	8674	0.92	668	10	9991
South-Eastern Asia	82404	63610	0.89	7061	25	37837
South-Central Asia	205614	11443	0.54	5218	5	20939
Eastern Asia	131376	43588	0.50	21794	5	8636
Asia	456225	127316	0.73	34741	10	85782
developing countries	899795	1612101	0.66	546511	21	424194

land potentially available. Even under these very mild conditions the populous region of South-Central Asia and the land-scarce Western Asia region are not likely to have enough suitable land resources to meet even only 5–10% of the required production increases from expansion of cultivated land, Western Africa reaching close to the limits.

Land cover change, in particular deforestation, has been identified as a key factor contributing to global environmental change (Turner *et al.* 1993). Alterations of the carbon pools, changes in albedo and the balance of sensible and latent heat fluxes, the impacts on total runoff and runoff speed, and the concern about loss of ecological complexity and biodiversity have prompted the international research community to focus their attention on the impacts of land use and land cover change (Turner *et al.* 1995; Fischer *et al.* 1996). It is therefore of interest to assess the balance of land remaining when setting aside land with crop production potential which is currently covered by ecologically highly valued ecosystems such as forest or wetland ecosystems. If this condition were to be strictly applied, six out of eleven developing regions would not be able to meet the stipulated increases in cultivated land, as forests and wetlands cover, on average, about two-thirds of the balance of land with cultivation potential.

A detailed discussion of the availability of water resources and future water use is beyond the scope of this paper. Previous studies have been devoted to the subject of water resources such as those of Baumgartner & Reichel (1975), L'vovich (1979), Shiklomanov & Markova (1987), Falkenmark (1989), and Shiklomanov (1990). A comprehensive analysis and collection of data are contained in Gleick (1993). Kulshreshtha (1993) considers several scenarios of future water demand and supply at the national level.

As a crude measure of regional vulnerability with respect to water resources, we look at the regional levels of annual renewable freshwater water resources available per capita, and their change with respect to altered population levels. Countries are grouped into three broad categories with regard to the availability of water resources. Water experts suggest that regions with an annual renewable freshwater water resource of less than 1000 $m^3\ cap^{-1}\ yr^{-1}$ should be regarded as

Table 9. *Annual renewable water resources* (m^3 $person^{-1}$ yr^{-1})

region	1995	2030	2050
USA and Canada	18141	14386	14012
Eastern Europe	2403	2586	2749
Northern Europe	10858	10619	10771
Southern Europe	3580	3823	4287
Western Europe	2178	2170	2355
Russian Federation	28769	33400	37361
Japan	4374	4611	4993
Australia and New Zealand	31269	22826	21926
Caribbean	2806	1989	1779
Central America	7919	4908	4243
South America	30019	20267	18199
Eastern Africa	2351	982	745
Middle Africa	23563	9371	6885
Northern Africa	546	318	272
Southern Africa	1304	702	578
Western Africa	4966	2121	1628
Western Asia	1850	940	769
South-Eastern Asia	10883	7256	6460
South-Central Asia	3032	1879	1641
Eastern Asia	2282	1854	1834
Central Asia	4881	3353	2966

water-scarce. When water supply ranges between 1000 and 2000 m^3 cap^{-1} yr^{-1} water stress is likely to occur. Only at levels exceeding 2000 m^3 cap^{-1} yr^{-1} are regions considered to have abundant water supplies. Data reported by the World Resources Institute (WRI 1996) and population levels projected by the UN (UN 1997) were used to flag regions where population pressure may result in water stress as defined above. Table 9 shows the results of such classification for both developed and developing regions. In 1995, three of the less developed regions, namely Northern Africa, Southern Africa, and Western Asia are considered to experience water scarcity or stress. By 2030, this number increases to six, adding Eastern Africa, South-Central Asia and Eastern Asia. Western Africa would join the ranks of water-stressed regions between 2030 and 2050.

6. CONCLUSIONS

In this paper we have reviewed what is known and expected about future population development. Regional differences in demographic change were presented, and population increase was compared with estimates of the availability of land and water resources. From this analysis some key conclusions can be drawn. (i) The 1996 UN population estimates and projections indicate a 65% increase in the world's population between 1995 and 2050. (ii) Population numbers in developed regions will, on aggregate, remain approximately at the current level. All the growth will occur in less developed countries, where numbers will increase by more than 80%. (iii) There is a wide variation of projected population increases among less developed regions. The largest increases, in percentage terms, between 1995 and 2050 are projected for sub-Saharan Africa, namely in Middle Africa (240%), Eastern Africa (215%) and Western Africa (205%). These are followed by Western Asia (130%) and Southern Africa (125%). In absolute terms, however, the largest increase will occur in South-Central Asia: an addition of some 1.15 billion people during the projected 55 years. (iv) Most of the population growth will already have occurred by 2030. While there are many uncertainties involved when projecting demographic changes to 2050 and beyond, the projection methods are fairly robust and show little variation when applied to the next 2–3 decades. (v) An assessment of the extent of land with rainfed cultivation potential has concluded that land resources in less developed regions could allow crop production on some 2.5 billion ha. An estimated 900 million ha were under cultivation around 1990, leaving a balance of 1.6 billion ha. Some 30% of these extents are adjudged to be only marginally suitability due to severe soil and landform limitations, excessive wetness conditions or drought hazard. (vi) The distribution of land resources is rather uneven. Of the 1.6 billion ha of the balance of land with potential for rainfed crop production, almost half (47%) is located in Latin America, some 45% in Africa, and only 8% in Asia. (vii) Overall, it is estimated that two-thirds of the balance of land with rainfed cultivation potential is currently covered by various forest ecosystems, wetlands and mangroves. The respective percentages by region vary between 23% in Southern Africa to 89% in South-Eastern Asia. For Latin America and Asia the estimated share of the balance of land with cultivation potential under forest and wetland ecosystems is about 70%, in Africa it is about 60%. If these were to be preserved, the remaining balance of land with some potential for rainfed crop cultivation would amount to 550 million ha. (viii) In addition to the uneven spread of land and water resources time is an important factor as well. The rapid population growth during the next three decades will leave little time to develop land and water resources along a sustainable path. (ix) The regions which will experience the largest difficulties in meeting future demand for land resources and water, or alternatively have to cope with much increased dependency on external supplies, can clearly be identified from our analysis. Foremost among these are Western Asia, South-Central Asia, and Northern Africa. A large stress on resources is to be expected also in many countries of Eastern, Western and Southern Africa.

Recent initiatives to establish global monitoring and observation systems as well as national and international programmes to study the driving forces and impacts of land use and land cover changes will result in much improved information that will allow us to assess the conditions and prospects for expanding food production more precisely than was possible here. Our analysis demonstrates that such understanding is of utmost importance and urgency.

APPENDIX 1

Global ecosystems database (dataset WE1.4D)

The first column indicates the global ecosystems class (Kineman & Ohrenschall 1992), the second column the aggregation index used in this study. Class levels not listed are not used in the classification.

NR	IA	name	explanation
0	11	WAT	waters, including ocean and inland waters
1	10	CCX	city complexes
2	2	SSG	short or sparse grass/shrub of semiarid climates
6	4	TBE	temperate/tropical montane broadleaf evergreen forest
8	1	DMB	desert, mostly bare stone, clay or sand
16	3	BES	broadleaf evergreen scrub (commonly with #46 and #47)
17	11	ICE	antarctic ice, land or grounded shore ice
20	4	SRC	snowy, rainy coastal conifer
21	4	MBC	main boreal conifers
22	4	SNB	snowy non-boreal conifer forest
23	4	CDF	conifer/deciduous, snow persisting in winter
24	4	TBC	temperate broadleaf/conifer forest: with deciduous and/or evergreen hardwood trees
25	4	SDF	temperate-decidiuous forest, snow persisting in winter
26	4	TBF	temperate broadleaf forest: deciduous, semideciduous
27	4	NSC	non-snowy conifer forest
28	4	TMC	tropical montane complexes (tree & other)
29	4	TBS	tropical broadleaf seasonal forest, with dry or cool season
30	15	CFS	cool farmland & settlements
31	15	MFS	mild/hot farmland & settlements
32	4	RGD	rain-green (drought deciduous) forest
33	4	TRF	tropical rainforest
36	16	PRA	paddy rice and associated lands (part anaerobic)
37	16	WCI	warm/hot crops with extensive irrigation
38	16	CCI	cool crops with irrigation (variable extent)
39	16	CCP	cold crops, pasture, irrigation
40	2	CGS	cool (snowy) grass/shrub (including much 2)
41	2	MGS	mild/warm/hot grass/shrub
42	2	CSM	cold steppe/meadow +/− larch, scrub
43	2	SGW	savanna/grass, seasonal woods; savanna belts
44	8	MBF	mire, -cold peatland: sphagnum, grass-like and/or dwarf shrub
45	8	MOS	marsh or other swamp (warm–hot) salty/freshwater marsh, thicket
46	3	MES	mediterranean evergreen tree/scrub (winter rainfall)
47	3	DHS	dry or highland scrub/tree (juniper, etc.)
48	4	DEW	dry evergreen woodland or low forest (mainly Australia, S. America)
49	13	HVI	hot-mild volcanic 'islands' (variable veg.)
50	1	SBD	sand desert, partly blowing
51	1	SDS	semidesert/desert scrub/succulent/sparse grass
52	1	CSS	cool/cold shrub semidesert/steppe (sagebrush...)
53	12	TUN	tundra (polar, alpine)
54	4	TER	temperate evergreen rainforest (major forest and woodland)
55	14	SFW	snowy field/woods complex
56	14	FFR	forest/field complex with regrowth after disturbances
57	14	SFF	snowy forest/field, commonly openings are pasture and/or mires
58	14	FWG	field/woods with grass and/or cropland
59	3	STW	succulent and thorn woods
60	12	SDT	southern dry taiga (and other aspen/birch, etc.)
61	12	LT	larch taiga with deciduous conifer
62	12	NMT	northern or maritime taiga/tundra
63	12	WTM	wooded tundra margin (or mt. scrub, meadow)
64	8	HMW	heath and moorland, wild or artificial (grazed)
65	13	CNW	coastal: NW quadrant near most land
66	13	CNE	coastal: NE quadrant near most land
67	13	CSE	coastal: SE quadrant near most land
68	11	CSW	coastal: SW quadrant near most land
69	11	PDL	polar desert with rock lichens
70	11	GLA	glaciers (other polar and alpine)
71	1	SSF	salt/soda flats (playas, lake flats rarely wet)
72	9	MSM	mangrove swamp/mudflat (Africa only)
73	13	ISL	islands and shore waters in oceans and/or lakes
74	13	WAT	water (water/land complex)
75	11	UND	not defined

Appendix 1 (*cont.*)

# aggregate ecosystems		classes
1	DESERT	Cold and hot deserts, bare land, salt flats, etc.
2	GRASS	Various types of grass and shrub land
3	SHR/FO	Various types of scrubs and woodland
4	FOREST	Various types of evergreen and deciduous forests
8	SWAMP	Mires, marshes, swamps, heath and moorland
9	MANGR	Mangrove swamps
11	WAT/GL	Water, glaciers, antarctic ice, polar deserts
12	TND/TG	Various tundra and taiga areas
13	COASTL	Coastal areas
14	FRM/FO	Various farm/forest classes
15	FRM-D	Dryland farming areas
16	FRM-IR	Irrigated farmland areas

APPENDIX 2

Balance of land with cultivation potential

Explanations to table 6 and table 6*b*. For estimating the balance of remaining land with crop production potential we started by assessing the extents of land where climate, soils and landform were sufficiently suitable for cultivation of at least one major crop (labelled 'gross'), subtracting from these land units areas under legal protection (shown as 'protected'). Land required for habitation and infrastructure is estimated using 1990 population levels (shown as 'habit 90'), and by subtracting we form the net amount of land with cultivation potential (shown as 'net'). From this we subtract land known to be used for agriculture (shown as 'cultivated'). The data are from FAOSTAT (FAO 1996) and the FAO's AT2010 (FAO 1995) study; data for China have been compiled by the IIASA Land Use Change Project. This allows us to form the balance of land with rainfed crop production potential which is not yet under such use (shown as 'balance'). The next task was to identify the amounts of forest and wetland ecosystems (i.e. aggregate ecosystems classes 4, 8 and 9) within this balance. To achieve this, the result from overlaying the global ecosystems database (Kineman & Ohrenschall 1992) onto the land resources inventory was applied. The meaning of the respective rows in tables 6 and 6*b* is as follows: (i) % forest and wetland: percentage of forest and wetland ecosystems classes in respective land class; (ii) forest and wetland: extent of forest and wetland in the balance of each land class; (iii) other: extent of other ecosystems classes in the balance of each land class.

For instance, in South America some 714097 thousand ha of land with cultivation potential are assessed as being still available out of a total of 963525 thousand ha, i.e. 74.1% of the total land with cultivation potential is currently not used for crop cultivation. More than two-thirds of this, 68.8%, are classified as forest or wetland in the global ecosystems database.

Table 6*b*. *Estimated balance of land with rainfed cultivation potential in 1000 ha.*

	low rainfall area (LOW) 1000 ha	uncertain rainfall area (UNC) 1000 ha	good rainfall area (GOOD) 1000 ha	problem area (PROB) 1000 ha	gleysols and fluvisols (NFL) 1000 ha	total rainfed cultivation potential 1000 ha
Central America and Caribbean						
gross	1819	20704	32472	30645	8691	94331
protected	3	485	1096	2582	1043	5208
habit. 90	33	469	830	587	153	2073
net	1783	19750	30546	27477	7494	87050
cultivated	1171	7473	13940	10630	835	34049
balance	612	12277	16606	16847	6659	53001
% forest and wetland	43	71	82	83	79	80
forest and wetland	268	8576	13889	14667	5107	42506
other	344	3701	2717	2180	1553	10494
South America						
gross	14096	38835	150551	633066	126979	963525
protected	481	1536	9241	68295	12495	92048
habit. 90	222	596	1488	3604	745	6655
net	13393	36702	139821	561167	113739	864822

[*continued overleaf*

Table 6*b* (*cont.*)

	low rainfall area (LOW) 1000 ha	uncertain rainfall area (UNC) 1000 ha	good rainfall area (GOOD) 1000 ha	problem area (PROB) 1000 ha	gleysols and fluvisols (NFL) 1000 ha	total rainfed cultivation potential 1000 ha
cultivated	5409	15450	67234	53726	8906	150725
balance	7984	21252	72587	507441	104833	714097
% forest and wetland	29	34	50	72	76	69
forest and wetland	2276	7222	36197	366028	79279	491002
other	5708	14031	36391	141412	25554	223095
Eastern Africa						
gross	26078	70571	115022	54832	30540	297042
protected	4027	9680	14980	5862	6607	41155
habit. 90	403	1164	1973	1068	473	5081
net	21647	59727	98069	47903	23460	250807
cultivated	8394	15323	25852	10687	2579	62835
balance	13253	44404	72217	37216	20881	187972
% forest and wetland	44	75	72	71	61	70
forest and wetland	5778	33473	52121	26583	12778	130734
other	7475	10931	20096	10632	8103	57238
Middle Africa						
gross	7611	27700	105295	205781	63727	410113
protected	410	1029	6053	10031	5635	23157
habit. 90	42	190	821	2027	537	3616
net	7160	26481	98421	193722	57556	383340
cultivated	1423	5711	13204	21893	906	43137
balance	5737	20770	85217	171829	56650	340203
% forest and wetland	14	19	62	84	92	75
forest and wetland	817	3886	53259	143658	51952	253572
other	4919	16885	31958	28172	4698	86632
Northern Africa						
gross	20927	35583	24375	9865	16641	107390
protected	61	525	515	310	382	1793
habit. 90	279	436	477	132	206	1530
net	20587	34622	23382	9423	16053	104067
cultivated	14695	8397	8285	2215	2619	36211
balance	5892	26225	15097	7208	13434	67856
% forest and wetland	28	12	40	41	30	26
forest and wetland	1677	3232	6067	2945	3979	17900
other	4215	22992	9030	4263	9456	49956
Southern Africa						
gross	14173	11653	8118	9509	1774	45227
protected	878	36	0	6	236	1157
habit. 90	54	9	18	20	4	105
net	13241	11607	8100	9483	1534	43965
cultivated	2608	6036	4222	2964	20	15850
balance	10633	5571	3878	6519	1514	28115
% forest and wetland	33	8	27	9	53	23
forest and wetland	3502	452	1055	613	808	6430
other	7131	5119	2823	5906	706	21685
Western Africa						
gross	32118	50921	59786	56630	12358	211812
protected*	1072	3084	3631	2641	394	10821
habit. 90	524	1168	1375	1632	384	5084
net	30523	46669	54780	52357	11580	195908
cultivated	20837	19790	20021	25169	4495	90312
balance	9686	26879	34759	27188	7085	105596
% forest and wetland	12	31	23	63	51	36
forest and wetland	1164	8329	7869	17143	3581	38086
other	8521	18549	26890	10045	3504	67509
Western Asia						
gross	12245	12740	7411	6255	4920	43571
protected*	0	0	0	0	0	0
habit. 90	310	375	282	185	134	1285

* No data were available in this study.

Table 6*b* (*cont.*)

	low rainfall area (LOW) 1000 ha	uncertain rainfall area (UNC) 1000 ha	good rainfall area (GOOD) 1000 ha	problem area (PROB) 1000 ha	gleysols and fluvisols (NFL) 1000 ha	total rainfed cultivation potential 1000 ha
net	11935	12365	7129	6070	4787	42286
cultivated	8425	10093	6870	6673	1122	33183
balance	3510	2272	259	−603	3665	9103
% forest and wetland	100	85	88	90	89	92
forest and wetland	3510	1937	227	−545	3275	8405
other	0	335	32	−58	390	698
South-Central Asia						
gross	31756	84999	51595	29720	23761	221830
protected	594	1652	1860	831	359	5295
habit. 90	2138	6147	3947	2165	2468	16865
net	29023	77200	45789	26725	20934	199670
cultivated	24569	63052	45926	26279	22779	182605
balance	4454	14148	−137	446	−1845	17065
% forest and wetland	31	62	86	66	58	54
forest and wetland	1401	8782	−118	293	−1079	9279
other	3053	5366	−20	153	−766	7786
Eastern Asia						
gross	11	368	47109	108528	33329	189346
protected*	0	0	0	0	0	0
habit. 90	0	10	2077	9143	3168	14398
net	11	358	45032	99385	30162	174948
cultivated	3	1083	44479	58605	27190	131360
balance	8	−725	553	40780	2972	43588
South-East Asia						
gross	1165	7776	43280	87811	34988	175019
protected	0	1179	7317	9904	2183	20582
habit. 90	34	235	1987	3081	1402	6738
net	1131	6363	33976	74826	31403	147699
cultivated	31	2349	17051	43853	19120	82404
balance	1100	4014	16925	30973	12283	65295
% forest and wetland	100	85	88	90	89	89
forest and wetland	1100	3422	14842	27806	10873	58043
other	0	592	2083	3167	1410	7252

* No data were available in this study.

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Discussion

A. Young (*University of East Anglia, UK*). Several studies, including this one, have arrived at large 'land balances' of remaining areas being cultivable but not presently cultivated. Such findings seem to substantially overestimate available land, perhaps due to lack of reliable data on current land use. An alternative approach should be made, that of positively identifying the remaining areas of cultivable land, visiting sample areas to find its true extent, and giving particular attention to ascertain whether such land was already serving important purposes.

G. Fischer. The work reported in this paper is based on the agroecological zone (AEZ) assessment methods developed by the FAO and IIASA using updated and enhanced data sets and calculation procedures. The analysis distinguishes a very large number of geographically explicit map units processed in a geographic information system. It therefore allows for the location of land adjudged to have cultivation potential to be identified, as suggested in your discussion point.

We concur with your concerns regarding data quality. As we point out in the paper, there are major international efforts underway to improve the detail and reliability of regional and global data sets. New databases derived from satellite information are in the process of being released that will help to better identify the current land cover (and perhaps land use) of areas assessed as having cultivation potential. However, even with the data available to us at the time of the analysis we concluded that more than 60% of the land with cultivation potential appears to be covered by forest or wetland ecosystems.

Another aspect of your discussion point regards the difficulty of accounting for land currently under cultivation, which appears to be sometimes underestimated in official statistics. For some regions, for instance China, it was possible to use estimates of present cultivated land that deviate from officially published statistics but represent the best available knowledge. Also, it can be observed that the extents of cultivated land estimated in the FAO study *World agriculture: towards 2010* in several cases substantially exceed the official estimates. This was taken into account in our analysis.

P. Vlek (*University of Göttingen, Germany*). Can food deficits affect world population growth? Do the current UN population projections take into account negative feedbacks from possible shortages of food?

G. Heilig. Can food deficits affect world population growth? We know that recurrent famines have again and again decimated populations in various places. The Irish Famine, two Global Economic Crises, two World Wars (with millions of casualties and much suffering from food deficits), the Great Leap Forward in China (a euphemism that covered up the most massive famine in recorded history), the Bengali Famine and numerous African famines (such as in Ethiopia and Somalia) have all caused the death of many millions. These tragic losses have left deep marks in the age structures of certain populations–some of them still visible today, but they have not affected the *global* population increase.

On a local or regional level, food deficits can certainly slow down population growth, or even lead to population decline. It is also likely that food deficits have at least contributed to the eradication of whole civilizations. Some researchers, for instance, believe that the Mayas suffered from chronic food shortages and recurrent famines after they settled in the karstic lowland of Guatemala, which is not very suitable for agriculture.

On the global level, however, it is quite unlikely that food deficits have ever or will in the foreseeable future affect population growth for the following reasons. (1) The world food system is not anywhere near the limits of food production capacity. There are, of course, all kinds of food limitations and agricultural constraints—particularly the inability of governments in Africa to modernize the agricultural sector and infrastructure, or the failure of poverty elimination in parts of Latin America or India. Some countries and regions also have serious environmental constraints, such as the lack of soils and water in the desert states of Western Asia. But there is no immediate limitation of land, water or energy (for fertilizers) *on the globe*. The argument that local deficiencies of natural resources for food production are the cause of food (and population) crises is a concept of the nineteenth century. It not only underestimates the role of modern technology in agriculture, but also ignores the functions of international trade and economic globalization. Numerous densely populated countries have discovered that they can simply buy food on international markets if they have income from other sources—such as oil exploration, electronic industries, tourism, etc. (2) Even if some countries or even larger regions, for whatever reason, are unable to sustain their population, others will not automatically stop growing; at least not because of their neighbours' food deficits. There are many places in the world that could feed much larger populations than currently live there. South America, for instance, has vast land and water resources that could sustain a population many times larger. Russia and Canada are, compared to Europe, China or India, almost 'empty' countries full of resources. Were they properly managed, the large arable lands of the Ukraine could feed many more people (before the Second World War the Ukraine was a major food exporter to Western Europe). Parts of Africa are very thinly populated, despite huge resources of arable land, sufficient water, and adequate climate conditions.

Available statistics do not indicate any signs of a looming global food crisis big enough to affect world population growth. Today, average per capita food calorie supply is significantly higher than even 30 years ago (and certainly since the time of Robert Malthus); we eat more vitamins and better and more protein. Of course, there is still much hunger and under-nutrition in our world. But it is overwhelmingly not caused by natural limitations of food production, but by economic, social and political deficiencies in certain countries.

Do the current UN population projections take into account negative feed-backs from possible food supply shortages? No. The most recent UN population projections do not take into account possible food deficits in certain countries.

B. Tinker (*University of Oxford, UK*). Will there be enough time for the development of land resources and the necessary improvements in cultivars and agricultural practices, especially if there is global change?

G. Fischer. The analysis in our paper was mainly concerned with the availability of land and water resources relative to the expected population increases estimated in the most recent UN population projections. Our assessment has shown that some of the less developed regions will find it very difficult to locate and develop enough land resources for agriculture to cater for increased food production to match the expected population development. In view of the strong population momentum, the next 20–30 years appear to be most critical for achieving food security. It is our understanding that closing the wide gap between actual and agronomically attainable yields, especially in African countries, would bring about major improvements in agriculture. In many Asian countries, for instance China and India, where yield increases have already been realized in the past and additional cultivable land is at a premium, the breeding of improved cultivars and further gains in agronomic treatments will be crucial to safeguarding future food supplies. This will not happen by itself but requires sustained efforts in R & D and agricultural extension services. Global change impacts on agriculture, although still uncertain and difficult to estimate, are likely to put additional strain on agricultural producers, especially those of less developed countries in tropical and sub-tropical regions.

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