Working Paper

Improving Population Assumptions in Greenhouse Gas Emissions Models

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WP-96-99
August 1996

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Abstract

It is no surprise that population plays an important role in long-term models of greenhouse gas emissions and global climate change. Population represents both a primary scale factor for the size of the human economy and the fundamental unit at which societal welfare is measured.

This paper surveys the population assumptions in several important models of global warming in the 1990s, including energy models, integrated emissions models, and economic policy models. Choice of population inputs, the role of population variables in model equations, sensitivity analyses, and consideration of population policy are all described.

The paper finds room for improvement in the following areas: choice and provision of population projections, consistent treatment of age structure and urbanization, specification of relationship between per capita income and population, and the consideration of population policy in economic policy models. It is suggested that improvement in these areas would be greatly aided by interdisciplinary cooperation, especially between demographers, economists, and energy modelers.

Acknowledgments

The author would like to thank Warren Sanderson, Wolfgang Lutz, Landis MacKellar, and Brian O’Neill for helpful comments. Special thanks also to Marilyn Brandl for preparing the text.

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Introduction

Global warming is one of the few scientific problems with a wide enough spatial and temporal scale to truly require long-term global population projections. Global warming has also become the major paradigm for studying a wide variety of broader global change issues, including intergenerational and international equity, the ‘limits to growth’, and appropriate policy responses to environmental risk. For these reasons, models of anthropogenic global warming are arguably the single most important application of long-term global population projections today.

And yet there appears to be very little dialogue between the demographers who create global population projections and the global warming modelers who use them. On the one hand, emissions modelers have very specific needs from population projections of which demographers may be unaware. On the other hand, demographers have insights into the complexity of population change and population-economic-environment dynamics of which modelers could be making use. The aim of this essay is to briefly describe the population assumptions used in several important models of global warming and to outline some areas in which demographers and modelers might work together to improve the population assumptions in future global warming models.

The time appears ripe for such interdisciplinary cooperation for three reasons: 1) The majority of the models over the last decade have relied upon the World Bank population projection series, a series which has now been discontinued. As modelers look toward a new source of population projections, this is the natural time for both demographers and energy modelers to redefine desired criteria for population inputs. 2) There is growing recognition that emissions models are highly sensitive to uncertainty in exogenous parameters such as population, and that improving the treatment of this uncertainty is likely to be as important as improving the models themselves. 3) While several recent studies (i.e. Birdsall 1992; Cline 1992) have pointed out the important role that population policy might play in controlling greenhouse gas emissions, little formal work has yet been done to actually integrate population policy into models of policies to control global warming.

1. Models Surveyed

Table 1 gives a brief description of the models of global warming considered in this paper. Note that while these models are among the most widely used in global warming assessment during the 1990s, this is far from a complete survey. The models can be broken down into three general categories: Energy models, integrated emissions models, and economic policy models.

Table 1. Some global warming models in the 1990s.

Model	# of Regions	Time Period	Type of Model
Energy Models			
Edmonds-Reilly-Barns (ERB) (originally ORAU/IEA) *(Edmonds and Reilly 1985)* *(Edmonds et al. 1995)*	9	1995-2095	Macroeconomic model of emissions of CO_2, CH_4 and N_2O from energy
GREEN *(Burniaux et al. 1992)*	12	1985-2050	Applied general equilibrium model of CO_2 emissions

Global 2100 (*Manne and Richels 1992)* *(Manne et al. 1995)*	5	1990-2200	Macroeconomic optimization model of energy use. Produces CO_2 emissions from energy
Integrated Emissions Models			
Atmospheric Stabilization Framework (ASF)-EPA *(Lashof and Tirpak 1990)*	9	1985-2100	Engineering-economic integration of various regional models of GHG emissions from energy, agriculture, and industry
Atmospheric Stabilization Framework (ASF)- IPCC *(Pepper et al. 1992)*	9	1990-2100	Engineering-economic integration of various regional models of GHG emissions from energy, agriculture, and industry
IMAGE 2.0 (*Alcamo 1994)*	13	1990-2100	Integrated model of GHG emissions from energy, land use and industry
Economic Policy Models			
Cline cost-benefit *(Cline 1992)*	1	1990-2275	Cost-benefit model of long-term CO_2 emissions
Fankhauser (*Fankhauser 1994)*	1	1990-2220	Stochastic model of CO_2, N_2O and CH_4 emissions used to calculate marginal damages of emissions
DICE *(Nordhaus 1994)*	1	1965-2365	Optimal Ramsey growth model. Models ecological damages and abatement costs of CO_2 emissions from energy and CFC emissions

The energy models (ERB, Global 2100, and GREEN) focus on GHG emissions from energy, and in particular carbon dioxide (CO_2) emissions.[1] These models use macroeconomic relations to project future energy supply, energy demand, and GHG emissions from energy. They all quantify the economic costs of reducing emissions from energy. Their time scales range from 60 to 210 years.

The integrated emissions models surveyed (ASF-EPA, ASF-IPCC, and IMAGE 2.0) take a combined engineering-economic approach to projecting anthropogenic emissions of the various GHGs including carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and halogens. Regional models of land use, energy use, industry and deforestation are linked in a unified framework. All extend to the year 2100 and are highly disaggregated spatially. Note that the Atmospheric Stabilization Framework (ASF), originally developed by the US Environmental Protection Agency, is centered on an energy module which is a modified form of ERB. The ASF has been a particularly important model since its adoption by the Intergovernmental Panel on Climate Change (IPCC) as a tool for making emissions scenarios.

The economic policy models (Cline cost-benefit, Fankhauser, and DICE) use very simple relations to quantify the long-term economic and ecological costs associated with GHG emissions. These models have very long time horizons (230 to 400 years) and are spatially very coarse. They are designed to answer questions such as “To what degree should society make potentially costly investments in greenhouse abatement today for the benefit of future generations?”

The one thing that all the models have in common is that population is fixed exogenously, rather than driven by economic variables or environmental factors. Global warming models with feedbacks on fertility, mortality, and migration were not found; the current assumption appears to be that long-term economic and ecological feedbacks on demographic rates are simply too uncertain to model explicitly.[2]

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[1] An estimated 52% of 1990 greenhouse gas emissions (in carbon equivalent terms) resulted from energy use, 45% of which was in the form of carbon dioxide emissions (MacKellar et al. 1996, based on Pepper et al. 1992, and Houghton et al. 1994).

[2] The most well-known example of a global environmental model with an endogenous population is the World3 model used in Meadows et al. (1974, 1992). The carefully detailed demographic component of the model--which relates fertility and mortality to food production, per capita income, and environmental pollution--was one of the most highly criticized parts of the model (i.e. Van de Walle 1973; Nordhaus 1972).

Further description of the models and their population assumptions is given in Appendix A. The reader is warned that the discussion which follows is based largely on the examination of published documentation of these models. Hidden model relationships or assumptions not made explicit in this documentation may have been missed. The reader looking for more detail is referred to the modelers themselves, or better yet, to their computer code.

2. Population Inputs

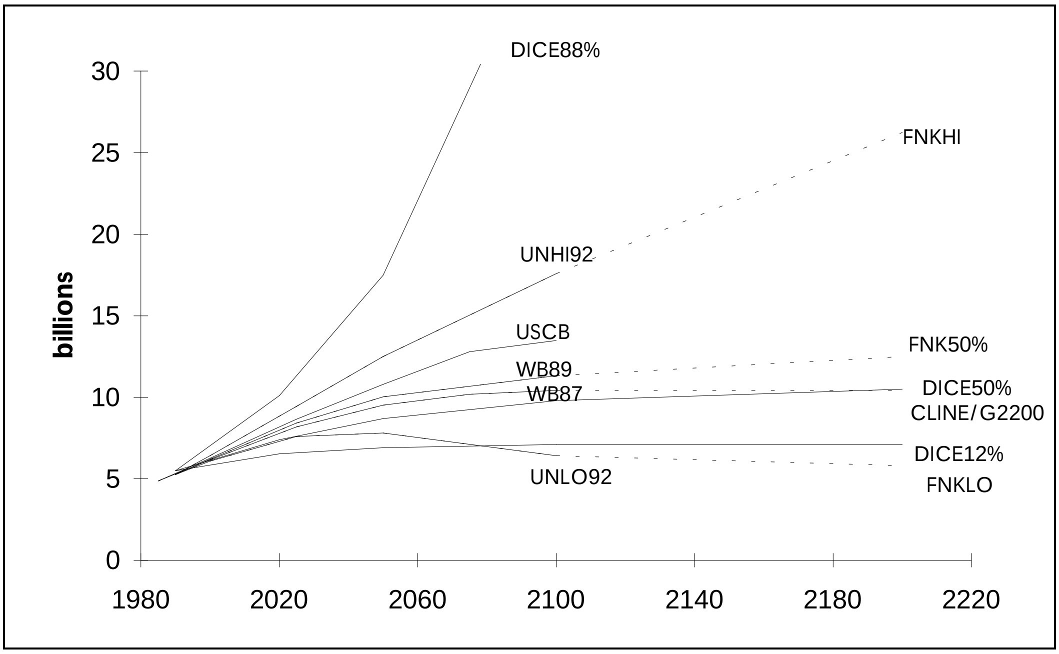
Projections used

Figure 1 and Table 2 show the population inputs used by the models. Note that several models (for example, ERB and Global 2100) have been reused and modified for a number of years. In these cases, the population assumption in the most recent application of the model available is listed.

With the exception of the algorithmic population specification in DICE, all of the models surveyed relied on age-structured, regionally-disaggregated population projections. The World Bank biannual projections were by far the most popular, and in fact the World Bank was relied upon in all cases where only one population projection was used. UN high and low fertility variants, and a projection from the US Census Bureau were used as alternative projections by the IPCC, and the EPA, respectively.

The most popular projection was the World Bank's 1987-1988 projection. This projection was used by both the EPA and the IPCC in 1990 emissions scenarios, and adopted by many of the models thereafter. This projection was also used in the OECD's 'model comparisons project' and the Energy Modeling Forum's 'EMF12' projects, two exercises which gave energy modelers standardized exogenous assumptions in order to facilitate model comparison (see Dean and Hoeller 1992).

Figure 1. Global population assumptions.



Key: WB87: World Bank 1987-1988; WB89: World Bank 1989-1990; UNHI92: UN medium-high 1992; UNLO92 UN medium-low 1992; USCB: United States Census Bureau 1987. CLINE, FNK, DICE, GLOBAL 2100: See Table 2.

Why have the World Bank projections been so popular over the other projections? In particular, why have the World Bank projections been consistently chosen over the similar series given by the UN? After all, the UN projections provide a projection which is similar in detail and methodology to the World Bank scenario--fertility approaches replacement worldwide by mid-century--but unlike the World Bank also provides high and low fertility variants. It is difficult to say how this preference emerged originally; it may be related to the fact that the UN publishes its full, regionally disaggregated scenarios only to 2050 (far too short for most global warming models), while the World Bank's standard volume includes results to 2150. In any case, at this point modelers appear drawn toward the World Bank projections in order to be consistent with past models and other studies. The IPCC certainly solidified this process with its selection of the World Bank projections for a preliminary emissions scenario in 1990, and its choice of World Bank population projections for its central scenarios in 1992. Cline cost-benefit, ERB, Fankhauser, and IMAGE 2.0 all directly cite their consistency with the IPCC when referring to their choice of the World Bank population projection.

Table 2. Model population inputs in the early 1990s.

Model	Year/Scenario	Projection	Comments
Energy Models			
ERB	1995	World Bank 1987-1988	After IPCC (1990)
GREEN	1992	World Bank 1989-1990	
Global 2100	1995	World Bank 1987-1988	Values held constant to 2200
Integrated Emissions Models			
ASF-EPA	1990		
	"Rapidly Changing World"	World Bank 1987-1988	
	"Slowly Changing World"	US Census 1987	
ASF- IPCC	1990	World Bank 1987-1988	
	1992		
	IS92a, IS92b, IS92e	World Bank 1989-1990	
	IS92f	UN medium-high 1992	
	IS92d	UN medium-low 1992	
IMAGE 2.0	1994	World Bank 1989-1990	After IPCC 1992 scenarios
Economic Policy Models			
Cline cost-benefit	1992	World Bank 1987-1988	After IPCC 1990 scenarios Values held constant to 2275
Fankhauser	1992		After IPCC 1992 scenarios
	Median	World Bank 1989-1990	Values extended to 2220,
	High	UN medium-high 1992	define 'triangular' probability
	Low	UN medium-low 1992	distributions
DICE	1994		Algorithmic, based on exponentially
	Median	NA	declining growth rates
	First quintile	NA	
	Fifth quintile	NA	

Sources: See Table 1. Most recent reference given is used.

3. The Role of Population in Model Equations

As a first approximation, the role of population in these models is quite simple: total population size proportionally scales total economic activity (i.e. GDP, transportation demand, agricultural demand), and hence emissions. This scaling role--labeled the ‘direct’ effect of population by Keyfitz (1992)--was the prime concern of Malthus, underlines the primary concern ecologists have about human population growth, and is often a useful simplification for both model construction and analysis.

However this simple relationship leaves out a number of more subtle *indirect* population-economic-environment interactions. Age structure, place of residence, and pace of population change may all have an impact on per capita economic activity and environmental impact. In the case of greenhouse gas emissions, for example, Preston (1994) has shown how including the effects of population growth on per capita income can substantially alter linear analyses. Similarly, MacKellar et al. (1996) have shown that aging and urbanization may have important effects on emissions projections. Finally, population may impact models through its effect on the relative welfare weighting of generations. This section describes how the surveyed models include such indirect effects.

Population composition effects: Aging

The projected aging of the LDC population in the coming century will yield a growth of adults, laborers, and households which is much more rapid than total population growth. LDC households, for example, are expected to grow nearly 1% faster than total population between 1990-2030 solely due to age-structure effects (MacKellar et al. 1995). To the degree that these demographic units are determinants of emissions it is important to incorporate them explicitly in models.

The potentially most important age-structure effect in the models arises from the demographic determination of economic output. With the exception of IMAGE 2.0 and the very long-term economic policy models, all of the models claim to determine GDP based on the *labor force* rather than the total population. Given this assumption, age structure would play an important role in model output; for example a change in population growth assumptions in these models would have very little effect on output and emissions in the first two decades after the perturbation. Unfortunately the actual computation of this ‘labor force’ tends to be either ad hoc, or exogenously fixed and unclearly specified. For example, in ERB (and hence the energy sector of ASF), labor force is crudely determined by the total population size 25 years previously (Edmonds et al. 1986b). In GREEN, no information at all is given regarding the relationship of ‘labor force’ in the model equations to the total population scenarios given in the model specification. In Global 2100, population and labor productivity assumptions must be combined outside of the model to yield total GDP.

Two other age-structure effects were also found. In the ASF-EPA scenarios, short-term residential emissions from energy are based on the number of households, which are calculated using exogenous assumptions of declining household size (Sathye et al. 1989). Again, the treatment of the demography is fairly ad hoc; because the household assumptions are defined independently from the population projections, the demographic futures are potentially self-inconsistent. The second age-structure effect was found in the ASF-IPCC scenarios, where deforestation is proportional to the population size 25 years earlier. Again, this lagged population size gives a crude estimate of the adult population.

It appears that while some of the models have made rough attempts to incorporate age-structure effects, the models are greatly hindered in this task by their lack of truly age-structured populations. Furthermore, in those cases where age-structure effects have been exogenously ‘hard wired’, the ability to alter population assumptions in the models and maintain consistent handling of age structure is severely limited.

Population composition effects: Urbanization

Urbanization, which brings a rapid expansion of demand for transportation, industrial, output and commercial services, is a key variable determining the level and type of energy demanded in the LDCs. Although data is sparse and rough, it is clear that urban households in LDCs use significantly less biofuels, and significantly more modern fossil fuels per capita than rural households at the same income level (Leach 1988; Fernandez 1980). In the LDCs, where the urban population is projected to grow at nearly double the pace of rural population between 1990-2030, accounting for this heterogeneity is potentially very important. Demand forecasts failing to do so risk overestimating future biofuel demands and underestimating future fossil fuel demand (MacKellar et al. 1996).

The models surveyed included little explicit consideration of urbanization, despite their widespread recognition of urbanization as an underlying cause of emissions growth. One exception is the ASF-EPA scenarios, which project short-term (1985-2030) residential energy demand using UN assumptions about regional trends in urbanization; the number of households using different fuel types varies proportionally to the level of urbanization in the region (Sathye et al. 1989). Another exception is the treatment of methane emissions from landfills and carbon emissions from biomass energy in IMAGE 2.0, both of which are scaled to urban rather than total populations.[3] Note that this latter assumption--justified on the basis that all rural biofuel use is sustainable and leads to no net carbon inputs to the atmosphere--appears to be in conflict with the conventional wisdom that because urban households use less biofuels per capita, third world urbanization decreases biofuel driven deforestation (i.e. Leach 1988).

Effects of population growth on per capita income

With few exceptions, emissions from energy and industry in these models are determined directly by GDP, not population. In 1990, emissions from energy and industry together made up 70% of all global emissions in carbon-equivalent terms (MacKellar et al. 1996). Thus the relationship between population and per capita income is probably the most important determinant of the form of the relationship between population growth and emissions. If more rapid population growth raises per capita income growth, then changes in future population sizes can be assumed to lead to more than proportional changes in emissions . If more rapid population growth lowers per capita income growth, then changes in future population sizes will lead to less than proportional changes in future emissions. Unfortunately, the form of the relationship between population and per capita income has been debated by demographers and economists with little consensus. This lack of consensus forms an important obstacle to understanding the true sensitivity of future emissions to population (Alcamo et al. 1994).

Table 3. Effects of population growth on per capita income growth.

Model	Short-term effect of population growth on per capita income growth	Long-term effect of population growth on per capita income growth
Energy Models		
ERB	Negative. Production determined by labor force age population	None
GREEN	Negative. Production determined by labor force age population*	Negative. Decreasing returns to population in production function
Global 2100	Negative. Production determined by labor force age population*	Negative. Decreasing returns to population in production function (nested CES function of capital, labor force, and energy)
Integrated Emissions Models		
ASF-EPA	Negative. Production determined by labor force age population	Negative, parametrically. High population growth associated with low income growth (“Slowly Changing World”). Low population growth associated with high income growth (“Rapidly Changing World”)
ASF- IPCC	Negative. Production determined by labor force age population	Positive, parametrically. Lowest population growth associated with lowest income growth (IS92c)
IMAGE 2.0	None	None
Economic Policy Models		
Cline cost-benefit	None	None
Fankhauser	None	None

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[3] Urbanization rates are extrapolated linearly from 1970-1990 rates and limited at an 85% level of urbanization.

DICE	None	Negative. Decreasing returns to scale in production function (Cobb-Douglas function of capital and population)

* Relation of ‘labor force’ input to the production function and population assumptions not clear from model documentation.

Table 3 summarizes the effect of population growth on per capita income growth in the models in the short- and long-term. For a given model, this effect is determined by the form of the *production function*, a function which determines output from a given set of inputs such as population (or alternatively, labor force) capital, environmental inputs or energy inputs. In many of the models such a function is central and explicit, and in all of the models it can be derived. The partial derivative of this function with respect to population determines the effect of population growth on per capita income.

In the short-term, models in which production is a function of labor force age population, rather than total population imply a very strong negative effect of population growth on per capita income. The effect arises because an additional infant decreases overall per capita income until it enters the labor force. In theory, as discussed in the previous section, many of the models incorporate this effect. Note that while this effect could be very important in some contexts because of time discounting, for long-term results it is likely to be less important. Also note that the specification is somewhat extreme to the degree that children on the margin do have some effect on production and consumption.

Of more general interest is the long-term relationship between per capita income growth and population growth. Many of the models--for example ERB, IMAGE 2.0, Cline cost-benefit, and Fankhauser--have simple production functions in which per capita productivity and population assumptions are exogenous and independent. In these models, there appears to be no long-term effect of population on per capita income. In contrast, DICE, Global 2100, and GREEN have production functions which exhibit decreasing returns to population scale. For example, consider the production function in DICE:

$$Y = AK^{0.25}P^{0.75}\,\Omega(\mu,\ E) \qquad [1]$$

where Y is GDP, A is exogenous technological progress, K is capital, P is population, and Ω represents the impact of global warming abatement costs and damages on output, a function of μ, the level of policy induced emissions controls, and E the total emissions. Equation [1] is a modified Cobb-Douglas equation where the factors of 0.75 an 0.25 represent the observed share of labor and capital in income. The equation implies that even in the absence of global warming damages and emissions abatement (Ω=1) an increase in population growth of 1% from the baseline yields a decrease in per capita income growth of roughly 1/4%.[4] In the presence of global warming costs (Ω<1), population growth reduces per capita income even further via the higher optimal control rates--and associated higher economic costs--which are induced by the greater population and economic size relative to the atmosphere.

In the case of the IPCC and EPA scenarios, per capita income and population are related parametrically through the definition of scenarios. Although both groups of modelers hypothesize negative correlations between population growth and per capita income, the scenarios they construct embody opposite approaches: The EPA scenarios include the negative correlation, combining rapid population growth assumptions with slow per capita income growth assumptions and vice-versa. The IPCC scenarios, in contrast, combine slow population growth assumptions with slow per capita economic growth assumptions and vice-versa, with the aim of presenting a wider range of possible emissions futures (Alcamo et al. 1994).

Intergenerational weighting effects

The three economic policy models, and Global 2100 are all fundamentally intergenerational models: Global 2100 and DICE are optimization models which maximize net utility throughout the entire model time period, while Cline cost-benefit and Fankhauser sum the welfare effects of global warming to present and future generations. In these models, population assumptions have an important effect on model results via their effects on the size of future generations.

The three economic policy models are based on maximizing what could be called a ‘Benthamite’ social welfare function (In DICE this maximization is explicit, in Cline cost-benefit and Fankhauser it is implicit in the

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[4] That is, the elasticity of per capita income with respect to population is -0.25. In other words, every additional person only produces 0.75 times the average output.

measurement of ‘costs’ and ‘benefits’ being summed).[5] The Benthamite social welfare function maximizes the “greatest good for the greatest number”, and can be written mathematically as follows:

$$Max(W) = Max\sum n(t)u(c(t),\cdot)e^{-\rho t} \qquad [2]$$

where n(t) is the population at time t, c(t) is the per capita consumption at time t, u() measures per capita utility, and ρ is the pure rate of time preference (potentially zero).

With a social welfare function of the form of [2], the rate of population growth has an effect which is equivalent and opposite to the effect of the pure rate of time preference. More rapid population growth raises the relative valuation of the future and vice-versa. For example, halving the ultimate level at which population stabilizes in these models would approximately double the welfare weighting of the current generation relative to the future. This is an important effect because while global warming damages will largely fall on future generations, much of the costs of avoiding global warming will be borne by current generations. Via this effect, more rapid population growth in the economic policy models tilts efficient policies in the direction of greater steps to control GHG emissions and to halt global warming.

4. Sensitivity Analyses to Population

Alcamo et al. (1994) have found that the main source of variability in emissions projected by energy models arises from ‘key model input’ assumptions such as population and productivity growth: The range of emissions projected by the models for 2100 is reduced from a factor of 40 to a factor of 2 if these exogenous inputs are harmonized. A natural conclusion is that uncertainty analyses with respect to such exogenous inputs are as important, if not more so, than further tuning of the models themselves. This section looks at those uncertainty and Monte Carlo analyses of GHG emissions models which have explicitly examined population inputs.[6]

Early analyses conducted by Nordhaus and Yohe (1983) and Edmonds et al. (1986b) found population a relatively *unimportant* source of uncertainty. The Nordhaus and Yohe study (NY83) conducted a Monte Carlo analysis on a simple economic-atmospheric model of CO_2 and found that population uncertainty ranked 7th and 8th among 10 ‘key parameters’ in explaining uncertainty in atmospheric CO_2 concentrations in 2100. Labor productivity and ease of substitution between fossil and non-fossil fuels were found to be most important.[7] The Edmonds et al. study (DOE86) conducted a similar Monte Carlo analysis on the ERB model (then IEA/ORAU) and found population uncertainty did not even enter the list of top ten variables which explain uncertainty over future levels of carbon emissions. As in NY83, labor productivity was again found to be overwhelmingly important.[8] These studies are still influential today in the climate change community, and were noted most recently by the IPCC (Alcamo et al. 1994).

It is of obvious interest to compare the ranges of population uncertainty used in these analyses to the other input uncertainties. In practical terms, it is easiest if we compare population to other stock variables whose size evolves through time. Of particular interest is labor productivity, which was overwhelmingly important in both analyses and as discussed above, acts in similar ways to population as a scale factor on output and emissions. Table 4 gives the difference in the growth rates between the high values and the low values of several stocks. Note that these ranges represent the 84% confidence interval in NY83 and the 94% confidence interval in DOE86.

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[5] Global 2100 maximizes a social welfare function which maximizes the utility of *total* consumption (measured by the logarithm of *total* consumption) through time. While the generational welfare weighting implied by such a welfare function is certainly dependent on population, the function corresponds to nothing in the literature on optimal population, and its relation to the maximization of *per capita* utility is unclear.

[6] Several important studies (i.e. Gruebler 1994) are based on sensitivity to GDP and fail to disaggregate GDP into per capita and population components.

[7] The study measured uncertainty using two indices: (1) the reduction in variance which occurs from holding the selected variable constant at its mean value, and (2) the variance arising from varying the selected variable alone. In both cases, the six variables more important than population were (1) substitutability between fossil and non-fossil fuels, (2) productivity growth, (3) substitutability between energy and labor, (4) extraction costs for fossil fuels, (5) costs of producing energy, and (6) airborne fraction of carbon emissions.

[8] Uncertainty was measured as an index of the variance in model output arising from varying the specified input alone. The four uncertainties which were found to be overwhelmingly important were: (1) labor productivity in the developing countries, (2) labor productivity in the developed countries, (3) exogenous energy efficiency, and (4) income elasticity of energy demand in the LDCs.

Clearly these studies simply find population a relatively certain variable. While productivity growth and other variables are assumed to have a wide spread of possible growth rates, differences in population growth rates are much more restricted (i.e. towards stabilization). This is particularly the case in DOE86 in which differences in annual labor productivity growth (-1% per year in the low assumption over 5% per year in the high assumptions) lead to massive differences in labor productivity by the year 2100, while population only differs by a factor of 1.5.

It appears that the findings by NY83 and DOE86 that productivity growth assumptions are overwhelmingly important while population growth assumptions are not important is largely a predictable result of the input uncertainty assumptions used. That is, taken over the long-term, variables with a larger spread of growth rates should naturally dominate the uncertainty. Indeed, if the input assumptions in Table 4 accurately represent the relative uncertainties, the underlying models would have to be extraordinarily sensitive to population in order for population to be an important source of uncertainty.

Table 4. Differences in high and low value, global growth rates.

	1975-2000	*2000-2025*	*2025-2100*	*Ratio of high to low value 2100*
NY83				
Population	0.6	1.0	1.0	4.1
Productivity	2.2	1.4	1.8	9.2
Price of non-fossil fuels	3.5	2.0	2.0	18
		1975-2100		*Ratio of high to low value 2100*
DOE86				
Population		0.4		1.6
Productivity		5.3		730
Exogenous energy efficiency		3.0		41

Source: Nordhaus and Yohe 1983; Edmonds et al. 1986b.

Thus one should not conclude from these studies that these given models are *insensitive* to population. As Edmonds et al. note, ERB is actually relatively quite sensitive to marginal population perturbations; considering perturbations of all parameters of 1%, population was found to be among the top five most sensitive variables in the model. Similarly, the model used by Nordhaus and Yohe should exhibit sensitivity to population that is similar to its sensitivity to labor productivity; these two variables are virtually analogous in the model equations, only differing by an exponent which is nearly one (the share of the economy which is not energy production).

If models are indeed sensitive to population, then where population is compared to variables with similar levels of uncertainty, population should be found to be an important overall source of uncertainty. Such is strikingly the case in a recent sensitivity analysis carried out by Nordhaus on DICE. In stark contrast to his 1983 study, Nordhaus finds the aggregated output of DICE to be *more* sensitive to population growth assumptions than any other variable, including exogenous productivity growth and the rate of time preference. A high value of future population growth (27 billion by 2100) approximately doubles the rate of optimal greenhouse gas abatement in the model, and nearly triples the optimal carbon tax (Nordhaus 1994).[9] This result appears to arise both from the use of the relatively substantial perturbation of population, and also because the DICE sensitivity analysis considers *all* model outputs, including the optimal control rate of GHGs and the savings rate. As pointed out above, these variables may be quite sensitive to population through intergenerational weighting effects. Kelly and Kolstad (1996) have shown similar results, outlining in particular the fact that low optimal control rates in DICE are critically dependent on the assumption of population stabilization.

Similarly O'Neill (1996) finds the IPCC and the EPA scenarios of GHG emissions from energy to be quite sensitive to population. Using a multiplicative framework, O'Neill finds that in the IPCC scenarios population uncertainty is significantly more important than uncertainty in either energy intensity or carbon intensity of GDP, although less important than uncertainty over future per capita income.[10] This ordering is consistent through time, and holds in the LDCs and the MDCs alike. In the EPA scenarios, which incorporated specific policy efforts to stabilize emissions, the population assumption is less important than the other variables in determining short-term emissions, but by 2100 is again second in importance to per capita income growth in determining emissions.

Derivation of probabilistic populations

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[9] The model was run with 'high' values (estimated at one standard deviation from the mean) and a sensitivity index--the sum of the percentage differences between key output values from their base case values--was computed.

[10] O'Neill fit the standard linear equation:

emissions = population * GDP/person * energy/GDP *carbon/energy

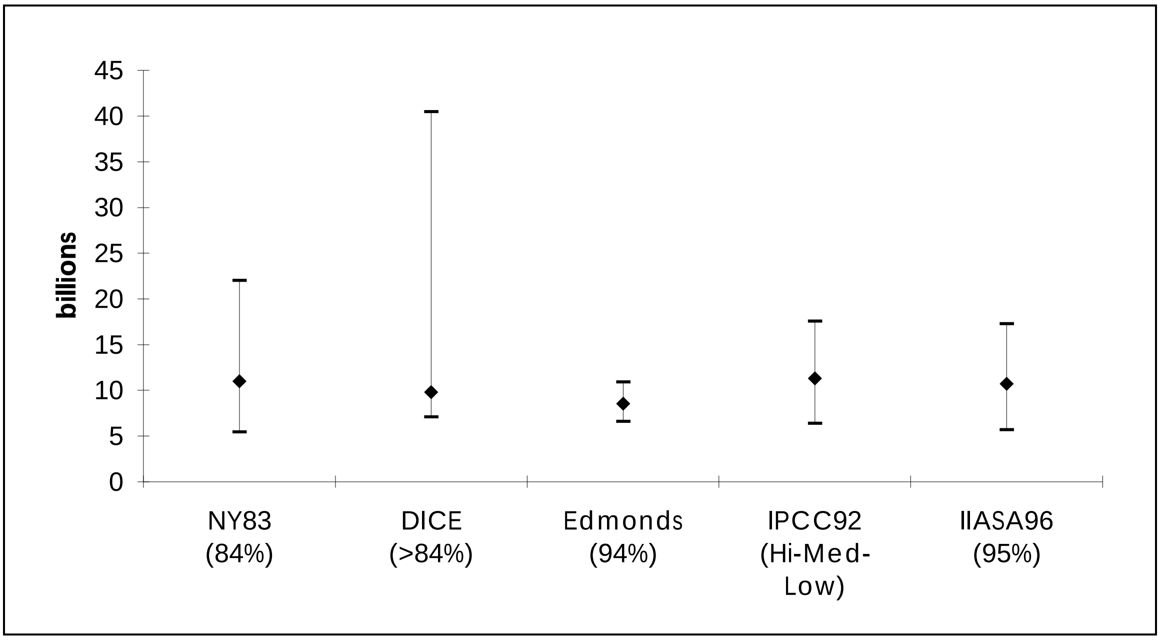
at the regional level for each set of scenarios. The percentage difference in global emissions due to varying a target variable from its high to low value was calculated for all high/low scenario combinations for the other three variables. The average of these results was taken as the index of uncertainty due to the target variable. For population, the input range is given by the UN 1992 medium-high and medium-low fertility scenarios used as high and low inputs by the IPCC. The input range of the other three variables are given by high and low assumptions implied by the scenario runs of the two models.

Given the important role the underlying uncertainty assumptions appear to play in driving sensitivity analyses, it is worth looking closely at these uncertainty assumptions and how they are derived. Figure 2 shows data on the probability distributions for global population in 2100 used by the uncertainty analyses discussed above. For reference, the median and 95% confidence bounds from recent probabilistic projections from IIASA's population group are also given (Lutz et al. 1996).

Note that the derivation methods and interpretations of these ranges differ greatly. The Nordhaus and Yohe study, DICE, and the IIASA study represent methodological attempts to explicitly derive future uncertainty. The population distributions in the Nordhaus and Yohe 1983 study and DICE are derived from six population projections from the late 1970s and early 1980s. Nordhaus and Yohe fit the growth rates in these projections to normal distributions and assumed that these distributions represented the underlying uncertainty over future *growth rates*, making a subjective increase in uncertainty for long-term values to account for expert 'consensus'. In the IIASA study, demographic experts were asked to specify full distributions of future levels of migration, fertility and mortality, as well as potential correlations between these variables. This expert data was used to generate stochastic populations based on the cohort component method.

In contrast, little justification is given for the DOE86 range and the IPCC range used by O'Neill and others. The DOE86 range used a published projection from Keyfitz as a median estimate and associated four other population paths with the 3rd, 17th, 83rd and 97th percentiles; no methodology other than 'subjective judgment' was given. Similarly, the UN projections bounding the IPCC range have no clear meaning or derivation procedure. It is only claimed that low and high fertility variants are "thought to provide reasonable and plausible future trends in fertility" and "usually thought to bracket the probable range of future population change for each country" (UN 1995).

Figure 2. World population in 2100, medians and ranges.



Sources: Nordhaus and Yohe 1983; Nordhaus 1994; Edmonds et al. 1986b; Pepper et al. 1992; Lutz et al. 1996 (confidence intervals given in parentheses).

The relative sizes of the ranges shown in Figure 2 are fairly consistent through time. The similar appearance of the UN-defined IPCC range and the IIASA range can be considered to be the demographers 'consensus' view of future population. In contrast are the restricted range of the Edmonds et al. study, and the much larger ranges of NY83 and DICE. The Nordhaus studies, it is interesting to note, are the only studies which do not preclude the possibility of continued long-term exponential growth of the population. The top quintile population assumption in DICE, for example, reaches a population size of 117 billion by 2100. Note that Nordhaus and Yohe have explicitly corrected their distributions to allow this growth in order to "account for [expert] tendency to move toward the current consensus."

5. Population Policy

Cline has made a very illustrative back-of-the-envelope calculation concerning population policy and global warming: Cline's analysis calls for a 4 GtC global cap on annual carbon emissions. Assuming that an averted birth removes a single person from a steady-state population of 10 billion, Cline calculates that the perpetual carbon emissions resulting from a birth amount to about 0.4 tC per year. Assuming carbon abatement costs of $175/tC, and discounting at between 2%-10% the resulting marginal benefit per birth averted today is between $700 and $3500. Cline's conclusion is that greenhouse limits provide an important rationale for greater population restraint.[11]

This theme has been taken up in more detail by Birdsall (1992) and Wexler (1996). Birdsall estimates a marginal cost of carbon abatement of $4-$12 /tC via fertility reduction in the LDCs from increased family planning expenditures and programs to educate girls. Comparing these costs favorably to estimates of marginal costs of technology-based carbon abatement, Birdsall concludes that "increased spending on population programs is likely to be part of any optimal carbon reduction strategy." Wexler (1996) provides estimates for the "greenhouse externality to childbearing", or the societal costs of all N_2O, CO_2, and CH_4 emissions resulting from a birth. Valuing IPCC IS92a emissions projections at a conservative $10/tC yields social costs of $850 per birth in the LDCs and $3,000 per birth in the MDCs.[12] More problematic scenarios of global warming yield costs of up to an order of magnitude higher.

The exercises mentioned above, and the sensitivity of models such as DICE to population raise obvious possibilities: Why not consider future population as a full policy variable in economic models of global warming? Why not create models that allow one to explore the economic effects of different population futures? This would be a powerful tool for population and environmental policy makers alike, allowing concrete estimates of the environmental benefits of lowered fertility paths.

A major impediment to economic models with endogenous population is that they lead to "different number problems", a category of problems for which application of standard welfare economics can lead to inconsistencies and paradoxes (Parfit 1984). That is, depending on population policy today there will be a different number of actors in the system which is being optimized. How is society to value those potential lives whose existence depends upon the population policies enacted today? Economists and philosophers have been unable to agree on an appropriate answer to the problem.

The question can be framed in terms of the choice of social welfare function, W, which is maximized. As discussed in Section 3, the three economic policy models surveyed here rely on a Benthamite social welfare function. When population is exogenous, the Benthamite criterion appears to be a natural and 'fair' choice for W because it values the utility of individuals equally, independent of the size of the cohort they belong to. However, with endogenous population the Benthamite welfare function places value on population growth for its own sake, an assumption that many people would find inappropriate. An obvious alternative is to adopt a welfare function that maximizes *per capita* welfare; unfortunately this, along with other suggested alternatives to the Benthamite function, tends to have theoretical problems as well. Appendix B describes some social welfare functions for endogenous population and their advantages and disadvantages.

A working definition of 'optimal' population--and an understanding of the values associated with it--must underlie any serious discussion of population policy, whether in economic models or otherwise. The long-term nature of economic models of global warming and their sensitivity to population scale brings this important issue into clearer focus.

6. Areas for Improvement

This final section outlines some concrete areas in which demographers and emissions modelers can work together to improve population assumptions in future models.

Future population inputs

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[11] Cline's point would be strengthened even further by more careful demography. Failing to disaggregate between the wealthy countries and the poorer countries seriously underestimates the benefit of MDC population restraint and overstates the benefit of LDC population restraint because per capita carbon emissions are about five times higher in the MDCs than in the LDCs. Furthermore, Cline's assumption that a single birth averted today averts a *single* person's emissions in the stationary-state causes him to understate the costs by a factor of about three; because generations overlap, averting a single birth today averts about *three* persons worth of annual emissions in the stationary population.

[12] Calculated at a discount rate of 2%, with children under the age of 15 assumed to cause no emissions.

With the World Bank discontinuing its population projection series, the question of which population projections future greenhouse gas emissions models will rely on is an open one. For reasons of consistency and standardization, it appears that the United Nations projections are most likely to be adopted. Thus it is a natural time to consider how the United Nations projection series currently meets global emissions modelers needs, and how it might be changed to better serve these needs. It is also a natural time to consider what role smaller scale demographic groups, such as at IIASA, might contribute to the creation of useful population projections.

Judging from the overwhelming popularity of the World Bank scenarios, especially the 1987-1988 projection, it appears that emissions modelers are very interested in consistent population assumptions which allow their models' results to be compared with one another. There appears to be less interest in using the most recent projection incorporating the latest fertility and mortality data. This suggests that much of the United Nations and World Bank resources directed toward bi-annual updates of population projections is of little use to global warming modelers. It would be interesting to survey the modelers directly on this point.

Of more use to global warming modelers would probably be more theoretical and empirical work aimed at creating usable and stable 'reference' projections for the models. In particular, two areas seem ripe for research: probabilistic population projections and projections associated with specific 'stylized facts' about the future of variables impacting population. Focusing on these two areas would, in different ways, mark a stark departure from the current practice of endlessly tuning exact point estimates of the actual future population.

Probabilistic population projections are likely to be increasingly demanded by emissions modelers. For highly uncertain, long-term environmental problems such as global warming, stochastic models are extremely useful. Stochastic models can be used for creating robust probability forecasts of environmental and economic futures (i.e. Fankhauser) as well as for sensitivity analyses aimed at determining research priorities (i.e. NY83, DOE86). Despite the difficulties inherent in making such projections, demographers will need to help provide such probabilistic projections to the best of their ability. Emissions modelers do require them, and--as illustrated in Section 4--will derive them on their own, if necessary.

As long as the UN attaches no explicit confidence bounds to its fertility variants, the UN population projection series will be of limited use for stochastic or uncertainty analysis. Users can only guess at what confidence intervals to associate with the UN variants. Thus independent demographers who are willing to develop methodology for probabilistic population projections may fill an important niche. The recent probabilistic projections by IIASA based on a wide variety of expert opinion provide an excellent example of the potential of this type of work.

In contrast to probabilistic projections, point projections associated with 'stylized facts' would place little emphasis on 'prediction,' and would instead provide modelers with a clear guide to the choice of appropriate population projections for scenario-based analyses. Possible 'stylized facts' might refer to variables such as per capita income growth, distribution of income, technological progress in health technologies, and environmental catastrophe. In this way, consistency of population assumptions with other scenario parameters will be much more likely to be achieved.

Note that in both cases, the robustness of the resulting population projections depends crucially on the inclusion of the widest possible range of experts in the exercise, including ecologists, economists, and virologists, as well as demographers. In the case of probabilistic projection, such broad-based efforts will insure against 'disciplinary consensus' about the long-term future, and help guarantee the use of the projections in a wide variety of applications. In the case of point projections associated with 'stylized facts' interdisciplinary construction of such scenarios will force scientists to rethink their visions of the future in terms of consequences and necessary conditions they may not have been previously aware of. The ecologist predicting rapid halting of population growth, for example, will be forced to confront the rapid aging and very low fertility rates required by such a scenario. In contrast, the demographer predicting continued high fertility will be forced to consider the associated increase in food production, strain on natural ecosystems, and increased atmospheric pollution.

Define the model relation between population growth and per capita income

The role of population in emissions models crucially depends on the long-term effect of population growth on per capita income growth. Ultimately total GDP, not population, is the variable that determines emissions from energy and industry. Thus continued research in the dependence of per capita income growth on population is of prime importance.

Several of the models surveyed included an implicit negative correlation between per capita income and population growth which arose in the production function. More attention should be given to this structure, and sensitivity analyses done to indicate the degree to which this negative feedback makes the model insensitive to population assumptions.

Other models with no functional connection between population and per capita emissions might benefit from parametric connections or flexible 'soft-links' by which productivity growth is related to population growth via modifiable elasticities. Even if no single definitive relationship emerges, modelers could at least begin to discuss the implications of various assumptions.

Consider population composition and use self-consistent scenarios

Various demographic characteristics other than total size may be viewed as the appropriate variables for projections of economic activity and emissions. Households, adult population, labor force, or urbanized populations, are a few obvious possibilities with relevance for emissions. In some cases, appropriate assignment might be as important as the choice of population projection itself: In the LDCs, for example, growth in the number of adults, the number of households, and the urban population between 1990-2030 is projected to outpace total population growth by 0.7% and 0.9%, and 1.4%, respectively. For the same period, the projected LDC total population growth rate only differs by 0.5% between the UN medium-high and medium-low variants.[13]

Because many of these compositional changes are highly dependent on age structure, it is important that projections are consistent with projected fertility rates. Short of incorporating age-structured population modules into their models, emissions modelers should at least use clearly documented, self-consistent demographic scenarios. Demographers could ease this task by including in population projection volumes base-year age-specific data on characteristics such as household headship and labor force participation, along with the projected age structures they currently provide.

Geographic composition is also important. Demographers, familiar by training with biases due to heterogeneity, are good at pointing out the importance of adequate geographic disaggregation. For example, Lutz et al. (1993) have shown that because of the inverse correlation between carbon dioxide emissions levels and population growth rates, a standard MDC/LDC breakdown can significantly overestimate future emissions. In the future, demographers may play an important role in testing model sensitivities to levels of regional aggregation and determining the minimum number of regions appropriate for a given model.

Include consideration of population policy in policy models

Demographers have an important role to play in allowing population policy to be considered seriously among policy options to control greenhouse gas emissions. At the very least, policy modelers require population projections which are linked to concrete population policy options; Bongaarts (1994) gives a good example of such a projection for the developing world. A further step would be the quantification of the population policy expenditures which separate such population paths. Although demographers may shy away from such uncertain and speculative calculations, they should be aware that even very rough estimates in this area will be very useful; cost estimates of abating emissions via technological change typically vary by more than an order of magnitude in any case.

Because of the ‘different number problem’ fully endogenizing population policy will present a serious challenge for economic models of global warming. On the other hand, it could be argued that this challenge is an unavoidable one. The philosophical difficulties of optimal population theory--how to value future generations, individuals, and population scale--are in fact central to an intergenerational, scale-dependent, environmental problem such as global warming. Thus there is a real need for collaboration between philosophers, ethicists, economists and demographers in order to make the largely theoretical literature on optimal population practically applicable to this important problem.

Conclusion

Because population acts as a scale factor across all anthropogenic activities and related emissions, a little refinement of the treatment of population in global emissions models can go a long way. Demographers and modelers need to work together to insure the appropriate handling of demographic heterogeneity, population composition change, and probabilistic population assumptions in global emissions models. Hard thinking also needs to be done about the valuation of unborn future individuals in economic analyses. These refinements will not only lead to improved emissions projections, but will also allow more thoughtful consideration of the implications of the threat of global warming on population policies.

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[13] Population and urbanization data from UN 1992-1993 medium projections. Labor force data from ILO (1986). Household projections from MacKellar et al. (1995).

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Appendix A. The Models and their Population Assumptions

Edmonds-Reilly-Barns Model (ERB)

The ERB model (originally IEA/ORAU) is a global model of energy use and greenhouse emissions from energy which has been frequently used over the last decades. The model projects energy use by supply technology and associated GHG emissions for nine world regions until the year 2095. A recent version of the model is described in Edmonds et al. (1995). Documentation of the model can be found in Edmonds et al. (1986a) and Edmonds and Reilly (1985).

The main role of population in ERB is through its effect on regional GDP, which is determined by projections of labor force population multiplied by exogenous productivity assumptions. Labor force population is defined as the population size lagged by one time period. Energy demand (E) in the non-OECD countries and the industrial sector of the OECD countries is a function of GDP, per capita income, and energy price:

$$E = P^{\beta_1} y^{\beta_2} Y \qquad [A1]$$

where P is an index of energy prices, y is an index of per capita GDP, and Y is total GDP.

For demand in the OECD residential and commercial sectors, however, energy demand is a direct function of population:

$$E = P^{\beta_3} y^{\beta_4} * \text{population} \qquad [A2]$$

The original IEA/ORAU model used population projections prepared by the demographer Nathan Keyfitz, which show world population rising to 8.5 billion by 2075. The most recent version of the model uses the World Bank 1987-1988 population projections.

GREEN

GREEN (General Equilibrium Environmental Model) is a twelve-region general equilibrium model developed by the OECD for analyzing the economic costs of policies to control CO_2 emissions from energy. Studies using the model have focused on taxation, trade, and international carbon agreements. A description of the model, along with various results, can be found in OECD (1992).

At each time step equilibrium prices and consumption levels of goods (including energy) are solved by equating demand to production. Energy fuels are included in the balance, resulting in emissions estimates of carbon dioxide. Population enters into the model in both the production function (through labor), and household demand. The base scenario of the model uses the World Bank’s 1989-1990 population projection, although the model has also been run using the World Bank’s 1988-1989 projection as part of the OECD model comparison project.

Global 2100

Global 2100 is a five-region macroeconomic model of energy use which computes carbon emissions from energy. Energy demand and supply is divided between various electric and non-electric technologies and is optimized through time in order to maximize intertemporal consumption. By constraining carbon emissions in the optimization framework, the model computes cost to the economy of various greenhouse gas emissions policies. The original model, Global 2100, is described in Manne and Richels (1992). The current version of the model, extended to 2200, is described in Manne et al. (1995).

Population enters in the Global 2100 model through the exogenous input of labor force “in efficiency units” (defined as population multiplied by potential productivity) into the regional production functions. The production functions are nested CES (constant elasticity of substitution) functions of the following form:

$$Y = (a\, K^{\alpha\rho} L^{(1-\alpha)\rho} + b\, E^{\rho})^{1/\rho} \qquad [A3]$$

where Y is production, K is capital, L is the labor force in efficiency units, E is energy and ρ and α are elasticities of substitution between the factors. In Global 2100, rising energy prices which limit capital investment or carbon dioxide limitations which limit the growth of energy inputs or capital inputs have the effect of reducing actual per capita income growth from potential per capita income growth. Note that the effect of a change of population growth in this model is equivalent to the effect of a change in potential per capita productivity.

Both the original version of the model and the Global 2200 version base the exogenous calculation of labor force in efficiency units on the World Bank’s 1987-1988 population projections.

ASF-EPA and ASF-IPCC (Atmospheric Stabilization Framework)

Emissions scenarios used by the US Environment Protection Agency (EPA) and the Intergovernmental Panel on Climate Change (IPCC) are actually derived from a core model developed by the EPA, the “Atmospheric Stabilization Framework” (ASF). The ASF is a linked set of regional models in agriculture, energy, and land-use which divide the world into nine regions. The energy model is a version of the IEA/ORAU model (see above), which has been modified to interface with more detailed end-use energy models in the short term. Details about the ASF and the EPA scenarios can be found in Lashof and Tirpak (1990). Details of the IPCC scenarios and modifications to the model are in Pepper et al. (1992).

In most sectors of the ASF population simply scales economic activity up or down in linear relation to population size.[14] In some of these sectors, such as emissions from human wastes and emissions from agriculture, this leads to a direct linear relationship between emissions and population size. In other sectors, such as emissions from energy use and industry, the relation between population and emissions is affected by non-linear relationships between the level of economic demand and the greenhouse gas intensity of economic activity.

Deforestation assumptions are left unspecified in the model framework. The EPA uses exogenous scenarios, associating a rapid deforestation scenario with rapid population growth inputs, and a slow deforestation scenario with slower population growth inputs. The IPCC links deforestation linearly to the size of the population, lagged by 25 years.

The EPA constructs two sets of scenarios: the “Slowly Changing World”, with relatively slow economic growth and technological development, and the “Rapidly Changing World”, with more rapid economic growth and technological development. The “Slowly Changing World” is associated with 1987 population projections of the US Census that yield a global population of 13.5 billion by 2100. The “Rapidly Changing World” is associated with the World Bank’s 1988 projections of only 10.5 billion people by 2100, resulting from replacement fertility being reached by 2040 worldwide.

The IPCC constructs five different scenarios, with widely varying assumptions about economic growth, deforestation rates, and halogen usage. Three population projections are used. The ‘central’ scenario (IS92a) uses the World Bank’s 1991 population projections, which yield a 2100 population of 11.3 billion. Other scenarios use the UN medium-low projection (6.4 billion by 2100, based on convergence of fertility at below replacement levels) and UN medium-high (17.6 billion by 2100, based on convergence of fertility at above replacement levels).

IMAGE 2.0

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[14] An important exception is the IPCC scenarios for halogens which are exogenous and completely independent of either the size of the economy or population size. This lack of basic scale consistency is a serious flaw in the IPCC halogen emissions scenarios.

IMAGE 2.0 is a thirteen-region integrated economic-atmospheric model developed to evaluate the consequences of climate policies. The model is unique in that it directly links regional economic models with more fine scale grid models of the biosphere. Details of the model can be found in Alcamo (1994).

The role of population in IMAGE 2.0 is quite straightforward. Demand in agriculture, energy use, and industry is projected on a per capita basis for each region and simply scaled up by the appropriate population figures for the region. Outside of this linear effect on the scale of economic activity, population growth assumptions have no effect on the model. The only demographic subtlety in the model is that methane emissions from landfills and carbon emissions from biomass energy are scaled to *urban* rather than total populations.

IMAGE 2.0 uses only one population scenario, the World Bank's 1989-1990 population projections.

Cline cost-benefit

In 1992, Cline published an exhaustive and landmark study of the economics of global warming (Cline 1992). The study is centered around a simple cost-benefit model of greenhouse abatement which Cline uses to measure the cost-benefit ratio of an aggressive program to stabilize global carbon emissions at 4 GtC per year. Cline shows that moderate variations of assumed societal discount rates, the scope of expected economic damages, and the possibility of catastrophic economic damages, can easily shift the benefit-cost ratio above or below unity. Arguing in favor of relatively low discount rates, conservative sensitivities to temperature, and inclusion of low probability catastrophic events, Cline finds a program to stabilize global carbon emissions at 4 GtC per year justified.

The model is a one-region model which extends until the year 2275. Population growth, per capita economic growth, and baseline emissions growth are completely exogenous. Population growth follows the World Bank 1988-1989 projection with world population stabilizing at 10.5 billion.

Fankhauser

Fankhauser has created a stochastic simulation model, similar to the Cline cost-benefit model, to measure the expected marginal damages per unit emissions of the GHGs N_2O, CH_4, and CO_2. The model is a one-region model and extends for 230 years. Future economic activity (including population growth), atmospheric sensitivity to greenhouse gases, and economic damages due to temperature are all specified stochastically. For each stochastic run, the marginal economic damages of GHGs emitted in a given time period is calculated and the results are combined to form full probability distributions for the marginal damages of GHG emissions.

Fankhauser finds the mean marginal damages of CO_2 emitted in the 1990s to be $20/tC, with 95% of the values above $6/tC, and 95% of the values below $45/tC. Values rise with time and are shown to be sensitive to the pure rate of time preference, and the possibility of catastrophe as represented by the use of log-normal distributions for atmospheric sensitivity and greenhouse damage parameters.

Population enters into the Fankhauser model in two equations. In the first equation, business-as-usual growth of emissions of each GHG are determined by the linear relation:

$$g_t = c_t + f_t + y_t + p_t \qquad [A4]$$

where g represents the growth rate of emissions, and c, f, y, and p represent the rates of change of emissions intensity of energy, energy intensity of GDP, per capita income, and population, respectively. In the second equation, 'benchmark' economic damages (estimated economic damages for a doubling of atmospheric carbon dioxide concentrations) are scaled to the size of the population, per capita income, and the income elasticity of willingness to pay to avoid damage of type x (non-market or market):

$$\frac{K_{x,t}}{K_{x,t-1}} = (1 + \varepsilon_x y_t + p_t) \qquad [A5]$$

where K_x is the benchmark economic damage of type x and ε_x is the willingness to pay to avoid damage of type x.

Fankhauser uses a 'triangular' probability distribution to define the stochastic inputs, in which an upper and lower bound limit the distribution, and probability densities are linearly interpolated between these points. Population growth, p_t, is defined for three periods (1990-2025, 2025-2100, and 2100-2220) following the IPCC's 1992 scenarios: In each period, the upper and lower limit of the distribution is given by the growth rates of the 1992 UN medium-high and medium-low projection for the period, and the median value is given by the World Bank's 1989-1990 projection.

DICE

DICE (Dynamic Integrated model of Climate and the Economy) is a twelve-equation economic optimization model created by Nordhaus (1994) to compare the economic optimality of various responses to the greenhouse effect, ranging from immediate efforts to stabilize climate temperatures to no response. Using this model Nordhaus estimates the optimal level of greenhouse gas emissions abatement society should undertake. In his basic scenario this amounts to about a 10% reduction from baseline emissions growth over the next century.

DICE is a one-region model which models costs and benefits of carbon dioxide emissions from energy and chloroflourocarbons (CFCs) emissions for the next 400 years. Population and income are explicitly related by the following modified Cobb-Douglas equation which lies at the heart of the model:

$$Y = AK^{0.25}P^{0.75}\,\Omega(\mu,\ E) \qquad [A6]$$

where Y is GDP, A is exogenous technological progress, K is capital, P is population, and Ω represents the impact of global warming abatement costs and damages on output, a function of μ, the level of policy induced emissions controls, and E the total emissions. Constrained emissions are determined by the following accounting relation:

$$E = Y\sigma(1-\mu) \qquad [A7]$$

In DICE, total population grows exponentially at an exponentially declining growth rate, a form which approaches an asymptote. The base case assumption--a rate of decline in the global population growth rate of 0.2% per decade--yields a population of 9.8 billion by the year 2100, eventually stabilizing at a population size of 10.5 billion. A unique feature of the DICE study is its use of this algorithmic approach to generate a full probability distribution for future population size for sensitivity analysis of the model. This sensitivity analysis reveals that DICE outputs are more sensitive to the rate of decline of population growth than to any other variable.

Appendix B. Social Welfare Functions for Endogenous Population

This appendix describes some social welfare functions for endogenous population and the problems associated with them. In all cases n(t) is the population at time t, c(t) is the per capita consumption at time t, ρ is the social rate of time preference (potentially zero), and u() measures per capita utility.

Benthamite:

$$W = \sum n(t) u(c(t),\cdot) e^{-\rho t} \qquad \text{[B1]}$$

The Benthamite function has been adopted by Meade (1955) and Dasgupta (1969) in their studies of optimal population. A main advantage of the Benthamite function is the fair relative weighting of cohorts. The main disadvantage is its strong bias toward population growth and the fact that under certain conditions it can favor a Malthusian world of very high population size and low quality of life over a smaller population with a high quality of life. Parfit (1984) has called this the “Repugnant Conclusion” and forcefully rejects the Benthamite function.

Millian:

$$W = \sum u(c(t),\cdot) e^{-\rho t} \qquad \text{[B2]}$$

This approach, which traces back to the writings of John Stuart Mill, maximizes the average utility of individuals through time. This function was adopted by the majority of early writers on ‘optimum population’ (see Dasgupta 1969), and most recently by Pitchford (1974) and Samuelson (1975). The obvious benefit to the Millian function is that it places no value on population growth or shrinkage *per se*. A main flaw is that it discounts the utility of individuals who are members of large cohorts significantly. In practice, given the unavoidable momentum in the world population such a function would entail a substantial discounting of the welfare of future individuals. A serious theoretical flaw is also the problem of “mere addition” identified by Meade (1955) and Parfit (1984).

“Generationally weighted” Millian:

$$W = \sum \left(\frac{n(t)}{\sum n(t)} \right) u(c(t),\cdot) e^{-\rho t} \qquad \text{[B3]}$$

Equation [B3] avoids the bias against individuals of large cohorts inherent in the Millian function, and the most blatant bias toward population growth in the Benthamite function (when per capita utility is rising, equation [B3] favors population growth but the expression is largely immune to the Repugnant Conclusion because population growth would never be favored if it lowered per capita income below previous levels). Similar schemes with fixed generational weights might be also possible, for example, by using weights based on populations projected using replacement level fertility or probabilistic projections.

Rawlsian:

$$\mathrm{W = MIN(u(c(t,))e^{-\rho t})} \qquad \text{[B4]}$$

The Rawlsian function would guarantee the best conditions for the least well-off generation. Note that under this function society would not only be willing to reduce the quality of many future lives in order to improve the welfare of the worst-off generation, it would also be willing to forego such lives completely.

Note that in principle it might be possible for models to combine any of the above functions using a two-step process. For example, intergenerational allocations could be first computed for *given* population paths using a cohort-fair function of the form of [B1] or [B3], and the best outputs for each population path could then be compared using the growth neutral Millian form of [B2].