Global demographic trends and future carbon emissions

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Substantial changes in population size, age structure, and urbanization are expected in many parts of the world this century. Although such changes can affect energy use and greenhouse gas emissions, emissions scenario analyses have either left them out or treated them in a fragmentary or overly simplified manner. We carry out a comprehensive assessment of the implications of demographic change for global emissions of carbon dioxide. Using an energy–economic growth model that accounts for a range of demographic dynamics, we show that slowing population growth could provide 16–29% of the emissions reductions suggested to be necessary by 2050 to avoid dangerous climate change. We also find that aging and urbanization can substantially influence emissions in particular world regions.

climate change | energy | integrated assessment | population | households

Statistical analyses of historical data suggest that population growth has been one driver of emissions growth over the past several decades (1–3) and that urbanization (2), aging (3), and changes in household size (2) can also affect energy use and emissions. Demographers expect major changes in these dimensions of populations over the coming decades (4). Global population could grow by more than 3 billion by mid-century, with most of that difference accounted for by growing urban populations. Aging will occur in most regions, a result of declines in both fertility and mortality, and is expected to be particularly rapid in regions like China that have recently experienced sharp falls in fertility. The number of people per household is also declining as populations age and living arrangements shift away from multigeneration households toward nuclear families.

Despite these expectations, explicit analysis of the effect of demographic change on future emissions has been extremely limited (5). Early exploratory analyses considered only population size or total numbers of households (6, 7) and used simple multiplicative models (8) that did not account for important relationships between population and economic and technological factors. Furthermore, these early models used little or no regional disaggregation, an important consideration given that, with some exceptions including the United States, population growth tends to be highest where per capita emissions are lowest.

More recently, a large emissions scenario literature (9) has developed that informs a wide range of climate change analysis and related policy discussions. Model sophistication and scope has increased substantially over time. Scenarios typically span timescales of decades to centuries, include emissions of multiple gases and aerosols from a range of sectors, including land use, and consider a wide range of emissions drivers (10–12). They have been used to study possible emissions in the absence of mitigation policy as well as the costs and other consequences of emissions reduction strategies. Although nearly all scenarios include assumptions about future population growth, none has explicitly investigated the separate effect of demographic influences on emissions, with the exception of a few studies at the country level (13).

Here, we assess the global implications of demographic change by developing a set of economic growth, energy use, and emissions scenarios using an energy–economic growth model, the Population-Environment-Technology model (PET) (13).

Methods

The PET model is a nine-region dynamic computable general equilibrium model of the global economy with a basic economic structure that is representative of the state of the art in emissions scenario modeling (*SI Text* has further description and references). To best capture the effects of future demographic change, we take an approach based on building principles from demography into a dynamic economic model by distinguishing among a large number of household types by household age (defined as age of the household head), size (number of members), and urban/rural residence in each region. We draw on data from national surveys covering 34 countries and representative of 61% of the global population to estimate key economic characteristics of our household types. We use these estimates to calibrate parameters in the PET model that represent household demand for consumer goods, wealth in the base year, and labor supply over time. To test the effect of demographic change, we develop a set of global household projections and use these to drive the PET model, computing the associated effects on emissions outcomes.

In the PET model, households can affect emissions either directly through their consumption patterns or indirectly through their effects on economic growth in ways that up until now have not been explicitly accounted for in emissions models. The direct effect on emissions is represented by disaggregating household consumption for each household type into four categories of goods (energy, food, transport, and other) so that shifts in the composition of the population by household type produce shifts in the aggregate mix of goods demanded. Because different goods have different energy intensities of production, these shifts can lead to changes in emissions rates. To represent indirect effects on emissions through economic growth, the PET model explicitly accounts for the effect of (*i*) population growth rates on economic growth rates (14), (*ii*) age structure changes on labor supply (15), (*iii*) urbanization on labor productivity (16), and (*iv*) anticipated demographic change (and its economic effects) on savings and consumption behavior (17).

The household survey data that we use in the PET model (*SI Text*) include detailed information on income and expenditures that has not been previously used in emissions scenarios. We estimate differences in labor supply and consumption preferences across regions and household types (Fig. 1). Although there are some exceptions,

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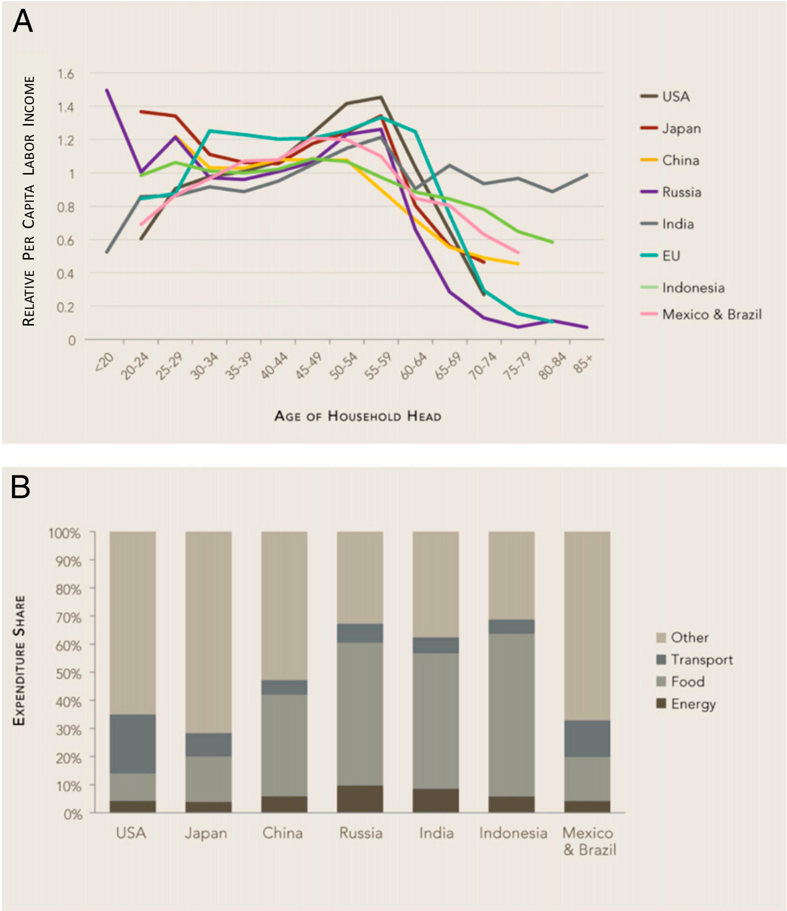

Fig. 1. Labor income per capita across household age, relative to the national mean (*A*), and household expenditure shares on four categories of goods (*B*) in the initial year of the simulations. Results are shown for national data used to characterize model regions. In the PET model, labor income data are used in the specification of exogenous labor supply, and expenditure shares are used in the calibration of household consumption preference parameters (in both cases, for household types defined by age, size, and urban/rural residence; *SI Text*).

households that are older, larger, or more rural tend to have lower per capita labor supply than those that are younger, smaller, or more urban. Lower-income households (e.g., rural households in developing countries) spend a larger share of income on food and a smaller share on transportation than higher-income households. Although labor supply and preferences can be influenced by a range of nondemographic factors, our scenarios focus on capturing the effects of shifts in population across types of households.

To project these demographic trends, we use the high, medium, and low scenarios of the United Nations (UN) 2003 Long-Range World Population Projections (18) combined with the UN 2007 Urbanization Prospects extended by the International Institute for Applied Systems Analysis (IIASA) (19) and derive population by age, sex, and rural/urban residence for the period of 2000–2100. To account for the impact of changes in rural/urban population age structures in key countries, we supplement these projections (which do not include separate urban and rural age structures) with our own projections for China and India, using a multistate population projection model with input assumptions based on the UN population and urbanization scenarios. In all regions, future population is further allocated into various types of households by rural/urban residence, size, and age of the household head based on projections that we carried out with an extended headship-rate household projection model (*SI Text*).

Results show that, relative to the medium projection, global population in the low and high scenarios differs by −1.5 to +1.7 billion in 2050 and −3.5 to +4.9 billion in 2100 (Fig. 2), with the largest proportion of these differences attributable to the other developing countries (ODC) region, India, sub-Saharan Africa, and China (Fig. 2 has a full set of regional definitions). Although a shift to older and more urban household types occurs in all regions, changes in urbanization levels are most pronounced in China, sub-Saharan Africa, and the ODC region. Changes in household age strongly affect the European Union (EU) and other industrialized countries (OIC) regions as well as Latin America. Household size changes are largest in India, ODC, and Latin America (*SI Text* has further details of household projection outcomes).

To test the effects of alternative demographic futures on emissions, we begin with two different baseline scenarios of future emissions that account only for the effect of population size changes, patterned after the A2 and B2 scenarios from the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) (9). As in the original SRES scenarios, we assume that population growth is high in the A2 scenario and medium in the B2 scenario. However, as discussed above, we do not use the population projections originally used by SRES, but rather, we substitute our own projections based on more recent projections from the UN. Using two baselines allows us to explore the effect of uncertainty in future socioeconomic conditions on our results. To reproduce key aspects of the A2 and B2 scenarios, we tune parameters that govern the effects of technical change on the productivity of labor and energy inputs in the PET model (*SI Text* has details of the tuning procedure) such that regional per capita emissions,

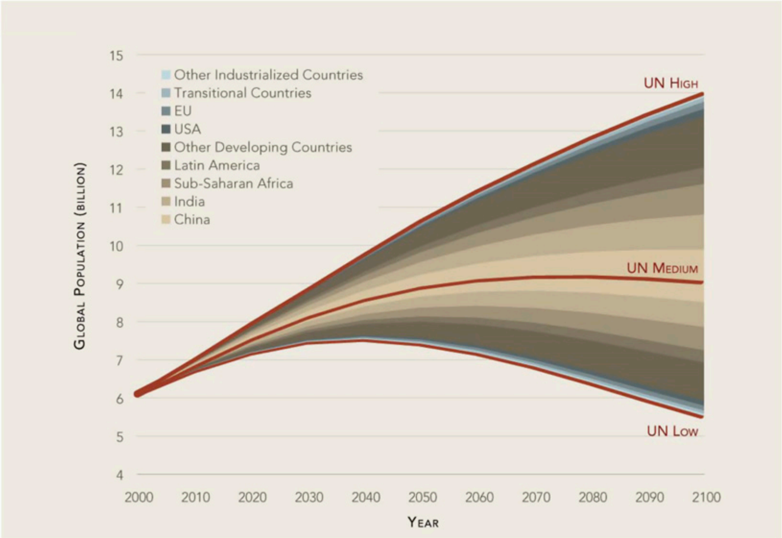

Fig. 2. Projected global totals (solid lines) and regional differences (colored bands) for population size. Individual colored bands indicate the contribution of each region to the difference between global scenarios.

gross domestic product (GDP), and primary energy use by source match values produced by the implementation of these scenarios in the IIASA Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) model (20).

We then produce two sets of variants of these scenarios. In one set, we assume that population size follows the same path as in the baseline scenarios, but we also account for the effects of compositional change due to (*i*) aging alone, (*ii*) aging plus changes in household size, and (*iii*) aging, household size, and urbanization combined. The net effect of each factor (i.e., aging, size, and urbanization) is calculated by comparing results across these three variants.

In another set of variants, we focus on the implications of alternative population growth paths by testing the effect of either a high or low population path in B2 (in contrast to the medium path in the baseline scenario) and a medium population path in A2 (in contrast to the high path in the baseline scenario). We use this set of variants to analyze the consequences of demographic change for economic growth and emissions, including the effects of aging, urbanization, and changes in household size. However, we do not assume a relationship in the reverse direction (i.e., changes in economic growth within these scenarios are not assumed to be necessary to produce alternative population paths). Uncertainty in the relationship between socioeconomic conditions

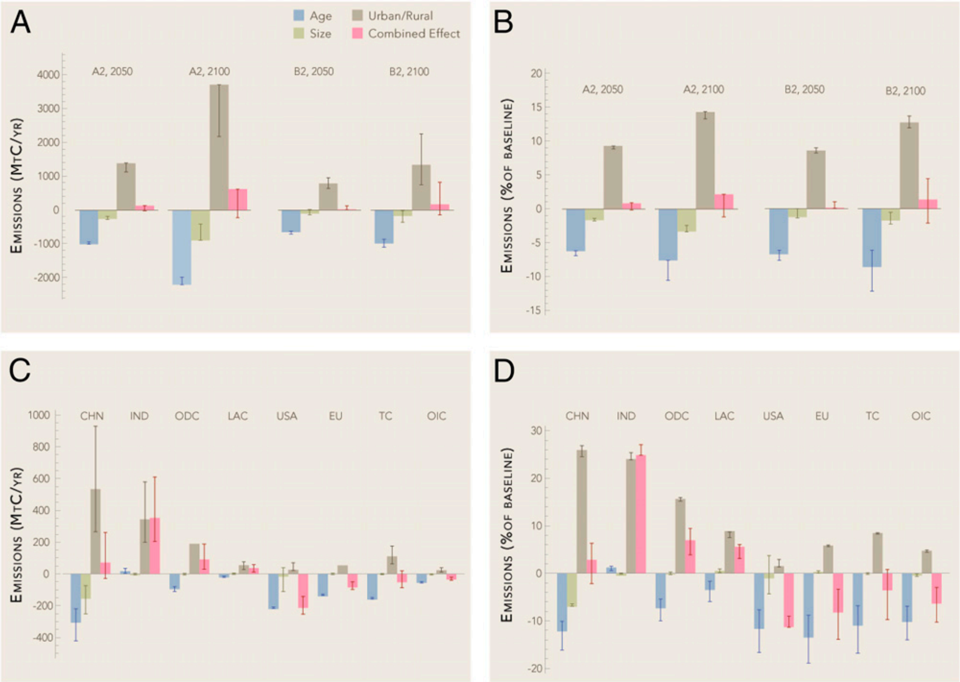

Fig. 3. Effect of population compositional change on emissions for the world (*A* and *B*) and by region (*C* and *D*; B2 scenario, 2100) in both absolute and relative terms. Effects shown are from changes in composition by age of the household head (age), household size (size), urbanization (urban/rural), and all three combined (combined effect). Bars show effects in the reference scenario, and uncertainty intervals show the range across all population scenarios.

and population growth allows for a wide range of population outcomes that can still be considered consistent with a given economic growth path, particularly for the B2 and A2 scenarios (21, 22).

Results

Results show that the effects of changes in population composition can have a significant influence on emissions in particular regions, separate from the effect of changes in population size. Aging can reduce emissions in the long term by up to 20%, particularly in industrialized country regions (Fig. 3). Aging affects emissions in the PET model primarily through its influence on labor supply. In the model, aging populations are associated with lower labor productivity or labor force participation rates at older ages, which (ceteris paribus) leads to slower economic growth. In contrast, urbanization can lead to an increase in projected emissions by more than 25%, particularly in developing country regions, also mainly through effects on labor supply. The higher productivity of urban labor evident in the household surveys implies that urbanization tends to increase economic growth. Although other studies find that, controlling for income, urban living can be more energy efficient (23), survey data for urban households include income effects and therefore result in increased emissions.

In most regions, changes in household size have little additional effect on emissions beyond those already captured by aging (older households are also typically smaller). This result could be because of limitations in our household projections, which include household size changes driven by aging and urbanization but only capture the effects of behavioral change on household size in China and the United States (*SI Text* has details on household projections). In China, reduced household size leads to lower emissions, a direction of influence counter to previous results (2). The reduction is driven primarily by the fact that large households in older age categories typically have greater per capita labor supply (and income) than smaller households, because they include adult children of working age. Thus, aging, combined with a decline in household size, leads to a reduction in per capita labor supply as older households become composed primarily of the elderly.

At the global level, compositional effects are largely offsetting, although this is not true in all regions. In general, urbanization is the dominant compositional effect on emissions in developing countries, especially China and India, whereas aging dominates in the industrialized countries. Results for the A2 scenario are similar to those for B2 in percentage terms, although substantially larger in terms of absolute emissions (*SI Text* has A2 results). For example, urbanization in the A2 scenario accounts for an additional 4 billion

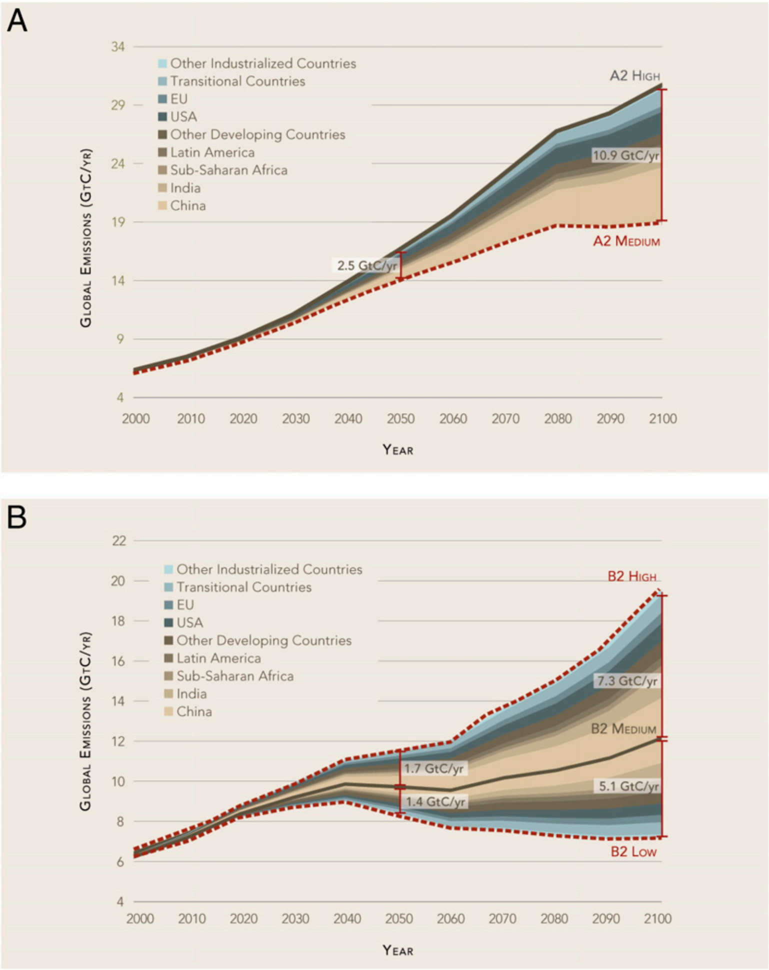

Fig. 4. Projected global totals (lines) and regional differences (colored bands) for CO_2 emissions. Individual colored bands indicate the contribution of each region to the difference between global scenarios. Solid lines shows emissions in the baseline scenario, and dashed lines show emissions in variants with alternative demographic assumptions. Both types of scenarios include the effects of changes in population composition by household age, size, and urban/rural status. Economic and technological assumptions are based on the IPCC A2 (*A*) and B2 (*B*) scenarios.

tons of carbon per year (GtC/y; about one-half of current global emissions) by 2100.

Results (Fig. 4) also show that if population were to follow the low path rather than the medium in the B2 scenario, emissions would decrease significantly, with a global reduction of 1.4 GtC/y in 2050 and 5.1 GtC/y in 2100. However, if population were to follow the high projection rather than the medium, global emissions would be increased by 1.7 GtC/y in 2050 and 7.3 GtC/y in 2100. Regionally, the most substantial portion of these changes in emissions comes from the developing countries; however, the contribution from the industrialized countries is not small. For example, change in US population growth has a pronounced effect on emissions, despite its small contribution to global differences in population outcomes, because of the relatively high per capita emissions implied in the B2 scenario. In the A2 scenario, results at the global level are larger in absolute terms: reducing population growth from the high to the medium path leads to a reduction of 2.5 GtC/y by 2050 and 10.9 GtC/y by 2100.

Discussion

Our analysis indicates that greater attention should be given in emissions scenarios to the implications of urbanization and aging, particularly in key regions of the world, including China, India, the United States, and the EU. This conclusion is motivated by the belief that better modeling of these trends would improve our understanding of the potential range of future energy demand and emissions. Better understanding of how fast (or slow) demand may grow is useful for informing response strategies. However, our results do not imply that policies influencing aging or urbanization themselves would be the most appropriate response. A wide range of considerations must come into play in designing mitigation strategies; the fact that a particular phenomenon is a quantitatively significant driver of emissions does not mean that it is also an important policy lever.

In addition, it is important to keep in mind that we use a broad definition of both urbanization and aging in this analysis. Urbanization, for example, is not limited to a geographic concept related to where people live and at what population density, with all other factors held constant. Rather, it represents both the growth of urban populations and a set of associated economic changes. In the PET model, urbanization has effects on labor supply and consumption preferences and therefore on economic growth and income. Some other analyses of the effect of urbanization on energy use or emissions abstract from any income effects and aim to measure the effect only of differences in lifestyles or consumption patterns (24–26). Thus, differences in conclusions about the effect of urbanization can be caused in large part by differences in the definition of urbanization.

Like urbanization, aging in this analysis is also associated with economic changes, including those related to reduced labor supply as populations age. We have assumed here that age profiles of labor supply remain constant over time at patterns observed in current household data. If these patterns do not remain constant, results will differ. For example, if retirement is postponed, labor supply at older ages will increase, and the emissions-reducing effect of aging that we find here will be lessened.

Our results also show that reduced population growth could make a significant contribution to global emissions reductions. Several analyses have estimated how much emissions would have to be reduced by 2050 to meet long-term policy goals such as avoiding warming of more than 2 °C (27) or preventing a doubling of CO_2 concentrations through implementation of a portfolio of mitigation measures characterized as "stabilization wedges" (28). Our estimate that following a lower population path could reduce emissions 1.4–2.5 GtC/y by 2050 is equivalent to 16–29% of the emission reductions necessary to achieve these goals or approximately 1–1.5 wedges of emissions reductions (*SI Text* has details of this calculation). By the end of the century, the effect of slower population growth would be even more significant, reducing total emissions from fossil fuel use by 37–41% across the two scenarios.

One caveat is that we have not made any assumptions about how reduced population growth occurs; rather, we treat alternative population growth paths as exogenous. Economic development is one factor that can facilitate declines in fertility and slower population growth. If it were assumed that increases in economic growth rates were driving fertility decline, our results would differ: faster economic growth would have an upward effect on emissions, offsetting the emissions reductions caused by slower population growth to some degree.

However, more rapid economic development is not the only factor, or a necessary one, in facilitating fertility decline. Policies can also significantly affect fertility trends. Although the appropriateness of policies that encourage even lower fertility in countries where it is already low is debatable and would require consideration of the tradeoffs associated with increased aging (29), in other regions, there are several such policies already considered desirable in their own right. For example, household surveys indicate that there is a substantial unmet need for family planning and reproductive health services in many countries. Policies that meet this need would reduce current fertility by about 0.2 births per woman in the United States (30) and 0.6–0.7 births per woman in the developing world (*SI Text* has details of this calculation). This reduction is comparable with the 0.5 births per woman difference in fertility assumptions between the population scenarios used here. In our analysis, emissions reductions in these regions (i.e., the United States and developing country regions other than China) amount to about one-half of the total reductions that result from following a lower global population growth path, suggesting that family planning policies would have a substantial environmental cobenefit.

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1. Dietz T, Rosa EA (1997) Effects of population and affluence on CO2 emissions. *Proc Natl Acad Sci USA* 94:175–179.
2. Cole MA, Neumayer E (2004) Examining the impact of demographic factors on air pollution. *Popul Environ* 26:5–21.
3. Fan Y, Liu L-C, Wu G, Wei Y-M (2006) Analyzing impact factors of CO2 emissions using the STIRPAT model. *Environ Impact Assess Rev* 26:377–395.
4. Cohen JE (2003) Human population: The next half century. *Science* 302:1172–1175.
5. O'Neill BC, MacKellar L, Lutz W (2001) *Population and Climate Change* (Cambridge University Press, Cambridge, UK).
6. Bongaarts J (1992) Population growth and global warming. *Popul Dev Rev* 18:299–319.
7. MacKeller FL, Lutz W, Prinz C, Goujon A (1995) Population, households, and CO2 emissions. *Popul Dev Rev* 21:849–865.
8. Ehrlich PR, Holdren JP (1971) Impact of population growth. *Science* 171:1212–1217.
9. Nakicenovic N, et al. (2001) *Special Report on Emissions Scenarios* (Intergovernmental Panel on Climate Change, Geneva).
10. Fisher B, et al. (2007) *Climate Change 2007: Mitigation of Climate Change*, eds Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (Cambridge University Press, Cambridge, UK), pp 169–250.
11. Clarke L, Bohringer C, Rutherford TR (2009) International, U.S. and E.U. climate change control scenarios: Results from EMF 22. *Energy Econ* 31(Suppl 2).
12. Alcamo J, et al. (2005) *Ecosystems and Human Wellbeing: Scenarios*, eds Carpenter S, Pingali P, Bennett EM, Zurek M (Island Press, Washington, DC), Vol 2, pp 297–373.
13. Dalton M, O'Neill BC, Prskawetz A, Jiang L, Pitkin J (2008) Population aging and future carbon emissions in the United States. *Energy Econ* 30:642–675.
14. Kelley AC, Schmidt RM (2003) *Population Matters: Demographic Change, Economic Growth, and Poverty in the Developing World*, eds Birdsall N, Kelley AC, Sinding S (Oxford University Press, New York), pp 67–105.

15. Bloom DE, Williamson JG (1998) Demographic transitions and economic miracles in emerging Asia. *World Bank Econ Rev* 12:419–455.
16. Ciccone A, Hall RE (1996) Productivity and the density of economic activity. *Am Econ Rev* 86:54–70.
17. Mason A, Lee R (2007) *Population Aging, Intergenerational Transfers and the Macroeconomy*, eds Clark R, Ogawa N, Mason A (Edward Elgar Publishing, Ltd., Cheltenham, UK), pp 128–159.
18. United Nations Population Division (2004) *World Population to 2300* (United Nations, New York).
19. Grübler A, et al. (2007) Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. *Technol Forecast Soc Change* 74:980–1029.
20. Riahi K, Grübler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol Forecast Soc Change* 74:887–935.
21. Mason KO (1997) Explaining fertility transitions. *Demography* 34:443–454.
22. O'Neill BC (2004) Conditional probabilistic population projections: An application to climate change. *Int Stat Rev* 72:167–184.
23. Dodman D (2009) Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environ Urban* 21:185–201.
24. Lenzen M, et al. (2006) A comparative multivariate analysis of energy requirements of households in Australia, Brazil, Denmark, India and Japan. *Energy J (Cambridge, MA)* 31:181–207.
25. Pachauri S (2004) An analysis of cross-sectional variations in total household energy requirements in India using micro survey data. *Energy Policy* 32:1723–1735.
26. Wier M, Lenzen M, Munksgaard J, Smed S (2001) Effects of household consumption patterns on CO2 requirements. *Econ Syst Res* 13:259–274.
27. Meinshausen M, et al. (2009) Greenhouse-gas emission targets for limiting global warming to 2 ° C. *Nature* 458:1158–1162.
28. Pacala S, Socolow R (2004) Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* 305:968–972.
29. Lutz W, O'Neill BC, Scherbov S (2003) Demographics. Europe's population at a turning point. *Science* 299:1991–1992.
30. Abma J, Chandra A, Mosher W, Peterson L (1997) *Fertility, Family Planning and Women's Health: New Data from the 1995 National Survey of Family Growth* (US Department of Health and Human Services, Hyattsville, MD).