The Future of Population

Joel E. Cohen

I propose to survey the main changes in the human population in the twentieth century and to look ahead to changes in the human population of the twenty-first century. Human populations interact strongly with their economies, environments, and cultures. I will touch on these interactions historically and prospectively.

To build modesty, I will consider the task of anticipating in 1900 the course of population in the twentieth century. Thus humbled, I will sketch one of the many possible worlds of the twenty-first century. Human choices will influence the human future.

This limited survey will concentrate on global description, though local and regional differences in populations, economies, environments, and cultures are important and often have consequences globally. Although the science of populations, including but not limited to demography, has advanced more in the twentieth century than in all previous centuries, this survey will omit the progress of the scientific study of populations.

Major Population Changes in the Twentieth Century

The twentieth century is likely to be unique in all of human history as the only century in which the earth's human population nearly quadrupled. The Earth's human population numbered between 1.6 billion and 1.7 billion around 1900. It numbered around 6.1 billion in 2000 (table 3.1). Looking backward from 1999's population of 6 billion, the most recent doubling of the human population took only 40 years. Never before the second half of the twentieth century (except possibly in the garden of Eden) had any human being lived through a doubling of

Table 3.1
Quantitative indicators of population, economics, the environment, and culture in 1900, 1950, 2000, 2050, and 2100.

Variable	Unit	1900	1950	2000	2050	2100	Notes
Population							
Aggregate population							
Population size	billion people	1.65	2.5	6.1	8.9	10.4	1
Low estimate	billion people				7.2	5.6	2
High estimate	billion people				10.8	17.5	3
Annual increment	million people	10	47	78	33	8	4
Population growth rate	%/year	0.61	1.88	1.28	0.37	0.08	5
Doubling time	years	114	37	54	187	901	6
Distribution of population							
% in "more developed" regions	% of people		32	20	13		7
U.S. population	million people	76	151	281	450	575	8
India population	billion people	0.24	0.36	1	1.53	1.62	9
China population	billion people	0.4	0.56	1.3	1.5	1.5	10
% of people in cities	%	13	30	47	61		11
Urban population	billion people	0.21	0.75	2.87	5.43		12
Urban centers of ≥10 million	number	0	1	20			13
% urban pop. in urban centers ≥ 10 million	% of people	0	1.6	9.6			14
Age structure							
Median age	years		24	26	38	40	15
Children (% <15)	%		34	30	20		16
Older persons (% 60+)	%		8	10	22		17
Mortality and fertility							
Life expectancy at birth	years (M + F)	30	46.5	66.5	76	81.7	18
Total fertility rate	children per woman		5	2.7	2		19
Environment							
Population density	persons/sq. km.	12	19	45	66	77	20
Population per permanent cropland	persons/ha	1.2	1.9	4.5	6.6	7.7	21
Atmospheric C emissions per person	tons C/year/person	0.3	0.7	1.2	(0.22, 0.33)	(0.15, 0.45)	22
Atmospheric C emissions	billion tons C/year	0.5	1.8	7.3	2.4	2.5	23
World water withdrawals	1000 km^3/year	0.5	1.3	(3.3, 4)			24
Nitrogen released in NO_x from fossil fuel combustion	million tons N per year	1.2	6.1	25			25
Nitrate mass fraction in ice	parts per billion	45	55	120			26
U.S. lead production	KtPb/yr	450	1100	1250			27
Net primary production	GtC/yr	46	47	52	62	74	28
CO_2 partial pressure	Pa	29	30	(34, 36.5)	48	70	29
Global average temperature	deg. C. annual	13.75	13.95	14.35			30
Land temperature	deg. C. annual	12.2	12.3	12.9	14	16.2	31
Economy							
GDP per person	1990 Geary Khamis dollars	$1,263	$2,138	$5,204			32
Size of the world economy	trillion (10^{12}) 1990 Geary Khamis dollars	$2.08	$5.35	$31.74			33
Culture							
U.S. persons per Senator	million people	0.84	1.57	2.75	4.50	5.75	34
U.S. persons per Representative	million people	0.19	0.34	0.63	1.03	1.32	35

Table 3.1 (continued)
Quantitative indicators of population, economics, the environment, and culture in 1900, 1950, 2000, 2050, and 2100.

Variable	Unit	1900	1950	2000	2050	2100	Notes
Primary education							
Northwestern Europe, N. America, Anglo Pacific	primary gross enrollment ratio (PGER)	72	107	103			36
Latin America, Caribbean	PGER	30	84	101			37
East Asia	PGER	21	94	110			38
Southeast Asia	PGER	4	71	104			39
Sub-Saharan Africa	PGER	16	54	85			40

Notes.
1. United Nations Population Division, briefing packet, 1998 revision, 14; Year 2100: *World Population Projections to 2150.*
2. Ibid.
3. Ibid.
4. Years 1950–2050: United Nations Population Division, *World Population Prospects: The 1998 Revision*, 2. Year 1900: United Nations Population Division, briefing packet, 1998 revision, 14. Year 2100: *World Population Projections to 2150.*
5. Computed from population size and annual increment.
6. Computed from growth rate.
7. United Nations Population Division, briefing packet, 1998 revision, 4.
8. Years 1900, 1950: U.S. Bureau of the Census, *Historical Statistics of the U.S., Colonial Times to 1970: Part 1*, 8, series A2. Year 2000: based on first results of Census 2000 at http://www.census.gov/main/www/cen2000.html. Years 2050, 2100, median of four "combined scenarios" from Dennis A. Ahlburg, and James W. Vaupel, 1990, "Alternative Projections of the U.S. Population," *Demography* 27(4): 639–652. Year 2100 figure is estimate for 2080.
9. United Nations Population Division, briefing packet, 1998 revision, 3. *World Population Projections to 2150*, 29. For 1900: Angus Maddison, *Monitoring the World Economy 1820–1992* (Paris: OECD, 1995), 114.
10. Ibid.

11. Year 1900: Brian J. L. Berry, "Urbanization" Pp. 103–119 (110, figure 7.8) in B. L. Turner et al., 1990, *The Earth as Transformed by Human Action*, Cambridge: Cambridge University Press. Year 1950: United Nations Population Division, *World Urbanization Prospects: The 1996 Revision*, 1 May 1997, 12. Year 2050: figure pertains to 2030; 13. Year 2000: *World Resources 1998–1999*, 274.
12. Calculated from percent of people in cities and total global population size.
13. United Nations Population Division, *World Urbanization Prospects: The 1996 Revision*, 1 May 1997, 103.
14. Ibid.
15. United Nations Population Division, briefing packet, 1998 revision, 27.
16. Ibid., 26.
17. Ibid.
18. United Nations Population Division, *World Population Prospects: The 1998 Revision*, 2. *World Population Projection to 2150*, 6, table 3. For 1900: Individual country life expectancies given by Angus Maddison, *Monitoring the World Economy 1820–1992*, 27, range from twenty-four years for India (low) to fifty-six years for Sweden (high) among twelve countries for which estimates are available. Global estimate of thirty years is from Samuel H. Preston (personal communication, April 1999).
19. For 1950–2050: United Nations Population Division, *World Population Prospects: The 1998 Revision*, 2.
20. Ibid. Estimates from population size for other dates.
21. Assumes 10 percent of all land can be used for permanent crops. One square kilometer equals 100 hectares.
22. Robert Engelman, *Profiles in Carbon: An Update on Population, Consumption, and Carbon Dioxide Emissions* (Washington, D.C.: Population Action International, 1998), 18, figure 6. Years 2050, 2100: estimated allowable emissions per person with high or low future population growth.
23. C emissions per person times total population. Years 2050, 2100: estimated allowable emissions per person with high or low future population growth.
24. 3.3 in 2000: *World Resources 1998–99*, (Oxford: World Resources Institute, Oxford University Press, 1998), 304. 4.4 in 2000: Sandra L. Postel, Gretchen C. Daily, Paul R. Ehrlich, 1996, "Human Appropriation of Renewable Fresh Water," *Science* 271: 785–788. Other figures: Peter H. Gleick, "The World's Water 1998–1999," graphed in *New York Times*, 8 December 1998, p. 7 of special section "The Natural World."
25. J. F. Muller, 1992, "Geographical Distribution and Seasonal Variation of Surface Emissions and Deposition Velocities of Atmospheric Trace Gases," *Journal of Geophysical Research* 97: 3787–3804. For 1900 and 1950: personal communication from J. F. Muller via Elisabeth A. Holland (2 April 1999). For 2000: extrapolation from estimates up to 1990.

Table 3.1 (continued)

26. Robert U. Ayres, William H. Schlesinger, Robert H. Socolow, "Human Impacts on the Carbon and Nitrogen Cycles" in *Industrial Ecology and Global Change* (New York: Cambridge University Press, 1994), 121–155. Page 126, figure 2, ice pack in South Greenland.
27. Robert Socolow and Valerie Thomas 1997. "The Industrial Ecology of Lead and Electric Vehicles," *Journal of Industrial Ecology* 1(1): 13–36. Page 23, figure 3, including primary and secondary production and net imports.
28. F. I. Woodward, M. R. Lomas, R. A. Betts, 1998, "Vegetation-Climate Feedbacks in a Greenhouse World." *Philosophical Transactions of the Royal Society of London* B 353: 29–39. Page 36, figure 10, simulations allowing feedback of vegetation on atmospheric CO_2 partial pressure and temperature.
29. Ibid. Page 36, figure 9, simulations allowing feedback of vegetation on atmospheric CO_2 partial pressure and temperature. High estimate for year 2000: J. A. Raven, 1998, "Extrapolating Feedback Processes from the Present to the Past," *Philosophical Transactions of the Royal Society of London* B 353: 19–28, 22, table 1.
30. Office of Science and Technology Policy, Executive Office of the President 1997, *Climate Change: State of Knowledge*, 7, figure 7, derived from data of Hansen et al. 1995, Goddard Institute for Space Studies.
31. Woodward, "Vegetation-Climate Feedbacks," 29–39. Page 36, figure 9, simulations allowing feedback of vegetation on atmospheric CO_2 partial pressure and temperature.
32. Maddison, *Monitoring*, 228. Year 2000 figure is GDP per person for 1990.
33. GDP/person times population size. Year 2000 figure uses 1990 GDP per person.
34. Number of states and representatives in 1900 and 1950 from: U.S. Bureau of the Census, *Historical Statistics of the U.S., Colonial Times to 1970: Part 2*, 1084, series Y216–217. Numbers of senators and representatives are assumed to remain fixed at 100 and 435, respectively, from 2000 onward.
35. Ibid.
36. James H. Williams, "The Diffusion of the Modern School," in *International Handbook of Education and Development: Preparing Schools, Students, and Nations for the Twenty-First Century* ed. William K. Cummings and Noel F. McGinn (New York, Tokyo: Pergamon, Elsevier Science, 1997), 119–136, 122, table 6.2. Year 1950 gives 1960 data. Year 2000 gives 1988 data.
37. Ibid.
38. Ibid.
39. Ibid.
40. Ibid.

the human population. Now everyone who is 40 years old or older has seen the earth's population double.

Some commentators who would minimize concerns about rapid population growth have suggested in the popular press that rapid population growth is, or will shortly be, over (Crossette 1997; Eberstadt 1997a, b; Laing 1997; Wattenberg 1997). Contrary to these suggestions, rapid global population growth continues (Gelbard and Haub 1998). This growth is driven principally by continuing high fertility in many developing countries. In a few countries that had high fertility in the recent past and presently have low fertility (such as China, Taiwan, Thailand, and South Korea), rapid growth in numbers is also driven by the very high proportion of young people.

To put present population growth in perspective, note that in 1900 the annual increment to global population size was 10 million people, with a growth rate of about 0.6 percent per year (table 3.1). In 1999 the estimated annual increment of population is about 78 million people per year (nearly 8 times larger), and the estimated annual rate of growth is approximately 1.3 percent per year (more than twice as large). For the less developed regions as a whole (about 80 percent of the world's population), the average woman would have 3.3 children in a lifetime at the estimated 1998 age-specific fertility rates (Population Reference Bureau 1998). If China were excluded from the less developed regions, the average number of children per woman at current fertility rates would be 3.8, sufficient to double a population in about 35 years. Announcing the end of the population explosion seems premature at best, deceptive at worst.

The extraordinarily rapid population growth of the twentieth century, especially in developing regions, produced a very high fraction of young people. During population growth, more people are added to a population (as infants) than die (generally as older people), so the proportion of young people increases. Contrast the age structure of the rapidly growing populations in regions called "less developed" by the United Nations Population Division (all regions of Africa, Latin America and the Caribbean, Melanesia, Micronesia, Polynesia, and Asia except Japan) with the age structure of the so-called more developed regions (North America, Japan, Europe, Australia, and New Zealand). In the less developed regions, the median age dropped from 21.3 years in 1950 to 19.0 years in 1970, then slowly rose to 23.2 years in 1995. By the end of the century, even after a third of a century of falling population growth rates, half the people in the less developed regions were less than 23 years old. By contrast, in the more developed regions, the median age rose steadily from 28.6 years in 1950 to 35.9 years in 1995 (United Nations Population Division 1999).

Rapid population growth also brought a very rapid movement of people from rural to urban areas. While the absolute size of the global population increased 3.8-fold during the century, the percentage of the population living in cities increased 3.6-fold (from 13 percent to 47 percent), resulting in a nearly 14-fold increase in the number of people living in urban areas (from perhaps 210 million in 1900 to nearly 2.9 billion in 2000).

The past half-century saw another major demographic event that is also without precedent in human history. Around 1965–1970, the global population growth rate reached an all-time high of 2.0 percent or 2.1 percent per year, and then declined by at least one-third to 1.3 percent or 1.4 percent (the higher estimates in both cases are given by Population Reference Bureau 1998, the lower by United Nations 1999). In the fourteenth century, the population growth rate fell because of increased deaths from plagues, war, and famine. By contrast, in the twentieth century, apart from the catastrophic effects of AIDS across the middle of Africa and the collapse of the economy of the former Soviet Union, life expectancies have increased almost everywhere, indicating overall better human health (Preston 1995). These increases in life expectancy are largely attributable to improvements in sanitation, diet, reductions of environmental hazards, behavior, and, to a limited extent, improvements in medical care. Unlike the fourteenth century, the fall in the population growth rate since 1965 has been caused largely by voluntary reductions in fertility, and the most important reductions have come in the poor countries, where a majority of the world's people lived and live. A detailed understanding of what drives major changes in fertility remains beyond the grasp of the social sciences.

Fertility is often measured by the period total fertility rate (TFR), which is the number of children a woman would have in the course of her entire lifetime if, at each age, she had the fertility rate that women of that age have in the current period. For the world as a whole, the TFR fell from approximately 5 in 1950 to 2.7 at the end of the century. This

striking reduction in fertility is the nub of fact behind the premature claim that the population explosion is over. The claim is premature because, in demographic terms, a TFR of 2.7 children per woman is much higher than the replacement level TFR of 2.0 or 2.1 children per woman. (To dramatize the demographic impact of differences in TFR of less than one child per woman, compare the 1998 high-variant and low-variant projections of the United Nations. If the TFR falls to 2.51 children per woman, the population by 2050 is estimated to be 10.67 billion. If the TFR falls to 1.56 children per woman, the population projected for 2050 is 7.34 billion. The difference in fertility over most of the period up to 2050 is smaller than the difference of 0.95 children per woman reached by 2050, yet the difference in population size in 2050 is 3.3 billion people, according to these projections.)

While 44 percent of the world's population lives in countries where the level of fertility is below the replacement level, what counts for global population growth is how far below replacement the low-fertility countries are, compared to how far above replacement the high-fertility countries are (in addition to the young age structure of countries that recently had high fertility). The balance of those distances below and above replacement, weighted by the relative sizes of the populations in low-fertility and high-fertility regions, determines whether global fertility levels lie above or below the replacement level. At the end of the twentieth century, the balance of high and low fertility still favors a rapidly rising population.

Both the speed of population growth since World War II and the dramatic fall in global fertility since 1965 are without precedent. The timing and magnitude of both events were not predicted by anyone. Why these colossal failures of prediction?

One may think about population as one vertex of a symmetrical pyramid in which the other vertices are the environment, economics, and culture (Cohen 1995). Any corner can go on top. One reason (though perhaps not the only reason) that no one foresaw the rapid rise in population after World War II and the fall in fertility starting around 1965 is that our scientific understanding did not, and still does not, encompass these four dimensions. Thinking in terms of this pyramid provides a checklist of crucial dimensions, though it will not eliminate uncertainty about the future.

Related Changes in the Twentieth Century in Economics

Economic growth during the twentieth century has more than quadrupled the average gross domestic product (GDP) per person, from less than $1,300 to about $5,200 (table 3.1). As population size nearly quadrupled during the century, the world's GDP grew roughly 16-fold. The GDP has serious limitations as a measure of economic well-being. To an important extent, the process of economic development substitutes market production for domestic production (Keyfitz 1993): eating in a restaurant replaces cooking at home; paying for childcare replaces parental rearing of children. Hence the GDP rises faster than real (including domestic) production. The GDP also includes commercial gains from market activities but neglects their drawing-down of environmental and social capital (Daly and Cobb 1989). Though the numbers that economists use to measure economic growth have uncertain interpretations as indicators of welfare, it seems clear that economic well-being has improved for many people during the twentieth century.

Not all the world's people shared in this dramatic improvement in average incomes. Between 1870 and 1985, the ratio of incomes per person in the richest countries to incomes per person in the poorest countries increased 6-fold, while the average absolute income gap between the richest and poorest countries grew from $1,500 to more than $12,000 (Pritchett 1995). Between 1960 and 1991, the ratio of income per person between individuals in the top one-fifth and the bottom one-fifth of the global income distribution rose from approximately 30-to-1 to more than 60-to-1 (United Nations Development Programme 1992, 34, 36). When the 1997 gross national product per person was adjusted for purchasing power parity, the low- and middle-income countries (with a combined population of 4.9 billion people) had $3,200 per person, while the high-income countries (with 0.9 billion people) had $22,800 per person (World Bank 1999, 191). Using purchasing power parity adjusted gross national product per person, the poorest 2 billion people on the planet have incomes of $1,400 per year, less than one-sixteenth of the average incomes of the richest billion. These comparisons of income between groups at different levels of economic development suffer from the same limitations as long-term comparisons of average GDP.

Related Changes in the Twentieth Century in the Environment

The economic and other collective activities of humans affect the planet far more than the sheer physical presence of humans. If the volume of all 6 billion humans were converted to soup and spread over the surface of the Earth, the result would be a film barely half a micrometer thick. Despite their small physical presence, humans have been a geological force on the face of the Earth since their mastery of fire hundreds of thousands of years ago. The intensity and diversity of human interventions in biotic and geological processes have grown enormously this century (Vitousek et al. 1997b).

The impact of human interventions on global biotic and geological systems is appropriately measured on an aggregate basis, although individual human well-being is appropriately measured per person. The reason is that the mass of the atmosphere, the area of the continents, the volume of the ocean, and other dimensions of the planet are independent of the size of the human population. For many planetary systems, human interventions are massive on a global scale. I shall mention as examples the global cycles of carbon, water, and nitrogen.

Atmospheric carbon emissions per person quadrupled from 300 to 1,200 kilograms of carbon per person per year between 1900 and 2000. Because population grew during the century, aggregate atmospheric carbon emissions rose from approximately 0.5 billion tons of carbon per year to 7.3 billion tons of carbon per year. (Tons are metric tonnes throughout.) In the steady-state, preindustrial global carbon cycle, the flux of carbon into the atmosphere from volcanic and tectonic sources was 0.2 billion tons of carbon per year, that from the entire land biota was 50 billion tons of carbon per year, and that from all sources was 191 billion tons of carbon per year (Watson and Liss 1998, 42, their figure 1). In this century human inputs of carbon into the atmosphere have changed from a negligible proportion to nearly 4 percent of all atmospheric carbon inputs. The partial pressure of carbon dioxide in the atmosphere rose in this century from 29 to 34–37 pascals. Atmospheric carbon dioxide concentrations are now higher than they have been in the last 150,000 years, a period that includes the emergence of modern humans and the multiple inventions of agriculture. The human and biological implications of this rise are hotly debated. Current models are the subject of controversy, some scientifically motivated and some politically motivated.

Between 1900 and 2000 (table 3.1), world water withdrawals grew from 500 cubic kilometers per year to levels variously estimated at 3,300 or 4,000 or 4,430 cubic kilometers per year, in addition to in-stream uses of 2,350 cubic kilometers per year (Postel, Daily, and Ehrlich 1996, 786, their figure 2). For comparison, the annual volume of available renewable freshwater probably lies in the range from 9,000 to 14,000 cubic kilometers per year. Postel et al. (1996) estimated "geographically and temporally accessible runoff" at 12,500 cubic kilometers per year. Thus, at the end of the twentieth century, humans withdrew annually from 24 percent (3,300/14,000) to 49 percent (4,430/9,000) of available renewable freshwater. The uncertainty in these estimates reflects current ignorance of humans' place in the world's water cycle. If in-stream uses are also considered, humans may exploit a majority of accessible renewable freshwater supplies and a substantial fraction of total global freshwater runoff (usually estimated at 41,000 cubic kilometers per year). This accounting does not consider other human uses of evapotranspiration.

In taking command of such a large fraction of freshwater runoff, humans have since 1950 constructed dams and reservoirs that impound more than 10,000 cubic kilometers of water, "as much water as there is total atmospheric moisture or equivalent to 10 times the Earth's biological water" (Chao 1995). The redistribution of this mass of water has measurably affected the rate of slowing of the earth's rotation and "has contributed a significant fraction in the total observed polar drift over the last 40 years" (Chao 1995, 3,529).

Human emissions of nitrogen in NO_x from the combustion of fossil fuels grew from 1.25 million tons per year to perhaps 25 million tons per year between 1900 and 2000 (table 3.1). The mass fraction of nitrates in ice grew from 45 parts per billion at the beginning of the century to 120 parts per billion at the end. Humans emit currently an estimated 40 percent of the nitrous oxide (N_2O), 70 percent of the ammonia (NH_3) and at least 80 percent of the nitric oxide (NO) emitted to the atmosphere from all sources (Vitousek et al. 1997a, 6, their figure 4).

Related Changes in Twentieth-Century Culture

Cultural changes in the last century have been no less dramatic than demographic, economic, and environmental changes. More people have had an opportunity to begin an education than ever before. Growing populations have generated increasing challenges to representative government. The gradual diffusion of the rights of citizenship has included unprecedented improvements in the status of women. These educational and civic improvements are correlated with, and may be causes of, declining fertility (Bledsoe et al. 1999).

One standard indicator of educational activity is the primary gross enrollment ratio (PGER). A gross enrollment ratio is calculated by dividing the number of children enrolled in school by the school-age population. Different countries define the ages of primary schooling differently. Because children who are over age or under age may also enroll in school, the PGER overrepresents the proportions of children of school age who are actually enrolled in school (Williams 1997, 122), and thus the PGER may exceed 100 percent.

In the wealthy regions of northwestern Europe, North America, and the Anglo Pacific, the PGER rose in the twentieth century from 72 percent to 103 percent. Latin America, the Caribbean, East Asia, and Southeast Asia saw much more dramatic increases, from as low as 4 percent in Southeast Asia to more than 100 percent in all these regions. Sub-Saharan Africa's PGER progressed from 16 percent to 85 percent. Late in the twentieth century, about three-quarters of the children eligible to attend primary schools in developing countries did so. The 130 million children who were out of school were disproportionately girls, and were mainly illiterate (Colclough 1993). These figures are probably no more reliable than are the demographic, economic, and environmental indicators quoted above.

Population growth poses increasing challenges to representative government. From 1900 to 2000, the number of people in the United States per U.S. senator grew from 0.84 million to 2.75 million, while the number per congressional representative grew from 0.19 million to 0.63 million. These increases probably understate considerably the relative increases in the number of voters per senator or representative. Women won the right to vote in the United States only in 1920. Moreover, the fraction of the American population in the age groups that are legally eligible to vote has probably increased from 1900 to 2000. Each senator and representative must try to listen to and speak to several times more people now than at the beginning of the century, even though a large fraction of the population does not vote. On the other hand, the means of communication to and from elected representatives, along with the cost and power of the mass media, have expanded enormously in the last century, so that purely demographic changes account for only part of the challenges to representative government.

In 1949 the British historian and sociologist T. H. Marshall identified three elements of citizenship: civil, political, and social. The civil element consists of individual freedoms: rights to personal liberty, freedom of speech, and religion; to property, contracts, and justice. The political element is the right to exercise political power as a voter and public official. The social element, for Marshall, meant "the whole range from the right to a modicum of economic welfare and security to the right to share to the full in the social heritage and to live the life of a civilized being according to the standards prevailing in the society." Marshall suggested that the formative period of civil rights occurred in the eighteenth century, of political rights in the nineteenth, and of social rights in the twentieth.

The improvement in the status of women in the twentieth century, and especially in its last third, may be the foremost example of the spread of the social element of citizenship. In 1946 the United Nations Commission on the Status of Women was formed to monitor and enhance the situation of women. The commission initiated a series of conventions: on the political rights of women in 1952, on the rights of women in marriage and divorce in 1957 and 1962, on the rights of women in employment in 1967, and by 1979 a Convention on the Elimination of All Forms of Discrimination against Women. These international conventions reflect aspirations more than achievements. By 1991 fewer than 5 percent of the world's heads of state, major corporations, and international organizations were women (United Nations 1991, 6–7).

For the mass of women, there were enormous changes. In the economically active population (consisting of those engaged in the cash economy, working for pay or looking for paying work), the number of women per 100 men rose from 37 in 1970 to 62 in 1990 globally (United Nations 1995). The increase in the economic activity of women was particularly dramatic in the developing regions of Asia and the Pacific, Latin America and the Caribbean, and Africa. Fertility fell sharply in these regions during the same years (although the decline was small in sub-Saharan Africa).

Half a century after Marshall spoke, the formative period of social rights is not yet over. The second half of the twentieth century saw the largest and fastest global increase of population ever to take place. Social

rights might have spread further and faster had population increase been smaller and slower during these decades. The argument behind this speculation is that when the supply of workers is reduced, as it was in Europe after the Black Death in the fourteenth century, workers are valued more highly, other things being equal (North and Thomas 1973). Of course, a rise in the economic value of workers has no necessary translation into an increase in the value of people as citizens. The relations of power in a society influence whether the economic scarcity of workers augments their civil, political, and social rights.

How Is Population Predicted, and How Well?

The first requirement of predicting the future of population size and composition is knowing how many people there are at the beginning of the projection. The estimate of the world population in 1950 changed 17 times in U.N. *Demographic Yearbooks* from 1951 to 1996. Nico Keilman (personal communication, 18 August 1999, extending Keilman 1999, 20) reported that there were 11 changes upward and 6 changes downward, while Bongaarts and Bulatao (2000, 42) reported 13 changes upward and 4 changes downward. Evidently there is some uncertainty about the uncertainty. Perhaps 20 percent of the world's population (a number roughly equivalent to the population of China) was not censused in the 1990s, though obviously such an estimate depends on a guess about how many people have not been counted (Bongaarts and Bulatao 2000).

The major approaches to population projection and their results are reviewed, with varying levels of skepticism, by Hajnal (1957), Cohen (1995, 107–157), Lutz et al. (1999), and the U.S. National Research Council (edited by Bongaarts and Bulatao 2000).

Two approaches to predicting future population are common: demographic and exogenous. A demographic approach ignores the connections of population with the rest of the world and forecasts the trajectories of demographic variables. One variation on this approach, mathematical extrapolation, assumes that future population sizes are determined by present and past population sizes, and nothing more. A mathematical curve is fitted to the total sizes of a population at past times. The formula is used to continue the curve into the future. A second variation on this approach, now called "cohort-component projection," was invented in 1895 by the English economist Edward Cannan (1895). It is still used in most official and academic population forecasts, for example, by the United Nations Population Division (Zlotnik 1999). It requires knowledge of future birth rates and death rates by age group. A third variation of the demographic approach recognizes the variability in past birth rates and death rates and incorporates stochastic processes into the cohort-component method.

The forecasting errors of past demographic projections were analyzed quantitatively in several studies (reviewed in Cohen 1986). Three simple lessons may be drawn. First, the longer the gap between the time a population forecast is made and the target date of the forecast, the lower the accuracy of the forecast. When they are accurate at all, population forecasts are usefully accurate for less than a generation (up to 20 or 25 years). Second, for short-term forecasts (up to 5 or 10 years), simple projection methods, such as assuming constant geometric growth, are at least as good as complicated ones. Third, and perhaps most important, forecasters generally underestimate both the uncertainty of the forecasts they produce and the instability of the core assumptions from which those forecasts are derived.

The National Research Council report (Bongaarts and Bulatao 2000) compares cohort-component projections of the population size of individual countries, regions, and the whole earth against the United Nations' 1998 estimates of historical population sizes. The projections were prepared by the United Nations Population Division in 1973, 1980, 1984, and 1994 for all countries; by the World Bank in 1972, 1983, 1988, and 1990 for countries belonging to the World Bank; and by the United States Bureau of the Census in 1987 for developing countries. Projected and estimated population sizes were compared at 5-year intervals from the starting date of each projection to 2000.

When individual countries are used as the unit of analysis, deviations between the initial population estimate used in the projection and the currently estimated initial population account for 60 percent of the difference between the projected and estimated population for a 5-year projection. For a 10-year projection, the error in the initial population estimate accounts for about 40 percent of the discrepancy between projected and estimated population; for a 20-year projection, about 20 percent; and for a 30-year projection about 10 percent. Starting with the right country population size is an important component of forecasting future country population, especially in the near term.

As in previous retrospective analyses of population projections, longer projections are less accurate than shorter ones. The mean absolute percentage error (that is, the mean value of the magnitude of the difference between projected and estimated population size, expressed as a percent of estimated population size) is about 5 percent for projections of 5 years. The mean absolute percentage error increases by about 2.5 percentage points with each additional 5 years between the base year and the target year for the projection. The mean absolute percentage error for 30-year projections is 17 percent. Individual projection errors may be larger. For example, in 30-year projections, 1 country in 4 has a projection error of at least 20 percent and 1 in 10 of at least 40 percent. These high error rates are due partly to errors in the initially estimated rates of birth, death, and migration, partly to misspecified trends in these vital rates, and partly to unanticipated external shocks, sometimes called "demographic quakes."

Exogenous approaches to population projection relate demographic variables to external variables that are presumed to influence or control the course of demographic variables. The exogenous approach rests on the hope that external variables can be better predicted than demographic variables (Cohen 1999). One variant of the exogenous approach is the system model, most famously illustrated by *The Limits to Growth.* System models posit quantitative interactions of population growth and size with nondemographic factors such as industrialization, agriculture, pollution, and natural resources.

Exogenous forecasts are little favored by most demographers, though Sanderson (1999) is an important exception. Exogenous forecasts are built on shifting sands. For example, one might hope to forecast the future of life expectancy (or any other demographic variable) as a function of future economic development, perhaps measured by average income per person. The relationship between income per person and life expectancy has changed notably in the twentieth century (figure 3.1). Over the decades of this century, a given level of income was associated with a longer and longer life. Using the relation between income per person and life expectancy observed around 1900 would have grossly underestimated the life expectancy of the poor and middle-income

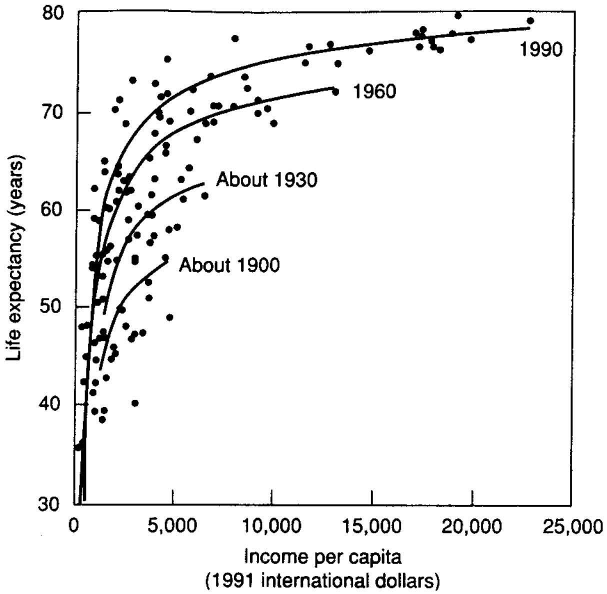

Figure 3.1
Relation between income per person and life expectancy at different periods. Source: World Bank 1993, 34, figure 1.9, attributed in part to Preston (1976).

countries by the end of the century, even if it had been possible to predict correctly their economic progress.

Much of the resistance by demographers to developing population projections that incorporate economic, environmental, and cultural interactions with demographic variables is due, not to the failure of empirical attempts to do so, but to an a priori disciplinary narrowness that inhibits many demographers from even trying.

Could Population Change in the Twentieth Century Have Been Predicted from 1900?

If someone in 1900 had tried to predict the course of the human population in the twentieth century, it seems unlikely that he or she could have succeeded. The fall of fertility during the Great Depression was not foreseen at the beginning of the twentieth century, to the best of my knowledge. During the Great Depression, some demographers and many public figures were concerned by the apparently imminent demographic collapse of the West (Teitelbaum and Winter 1985). Apparently no one

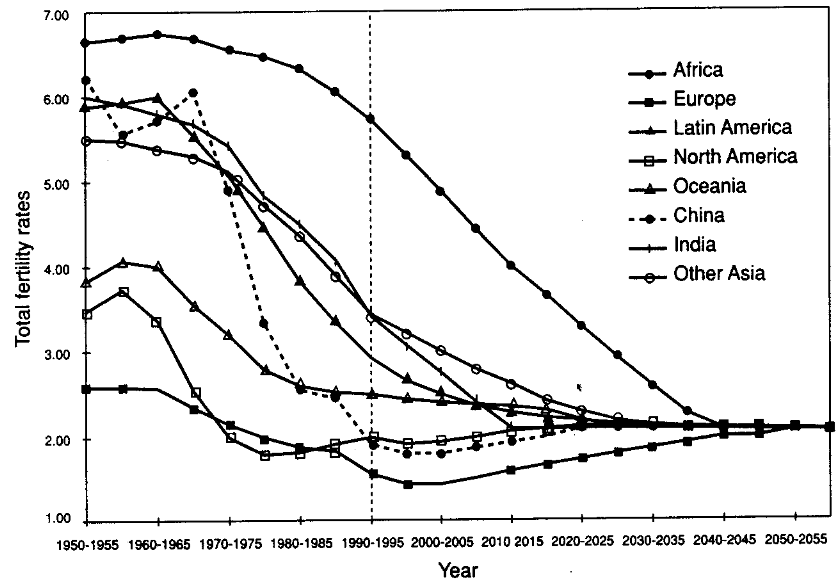

Figure 3.2
Total fertility rate (average number of children per woman's lifetime, at current age-specific birth rates) for major areas of the world, observed (to the left of the dotted vertical line) and anticipated in the medium-fertility scenario of the United Nations Population Division (1998b, their figure 1, 9). Reprinted by permission.

foresaw the baby boom in some Western countries after World War II. Some pre-war demographers anticipated a rising population in developing countries after World War II. However, all were surprised by the speed of decline in death rates and the magnitude of the subsequent rise in population. Apparently no one predicted that the global population growth rate would peak between 1965 and 1970. Nor was anyone able to forecast quantitatively the pace at which fertility would decline after 1970. The TFRs of different regions have varied widely across regions and over time (figure 3.2). The complexity of the observed pattern of TFRs (to the left of the dashed line in figure 3.2) contrasts starkly with the smooth simplicity assumed for the future (to the right of the dashed line).

In 1798, in an early example of an exogenous projection, Malthus assumed that population growth was limited by the area of arable land. For more than a century and a half after he wrote, the evidence appeared to confirm his assumption. As population grew, so did the area of arable

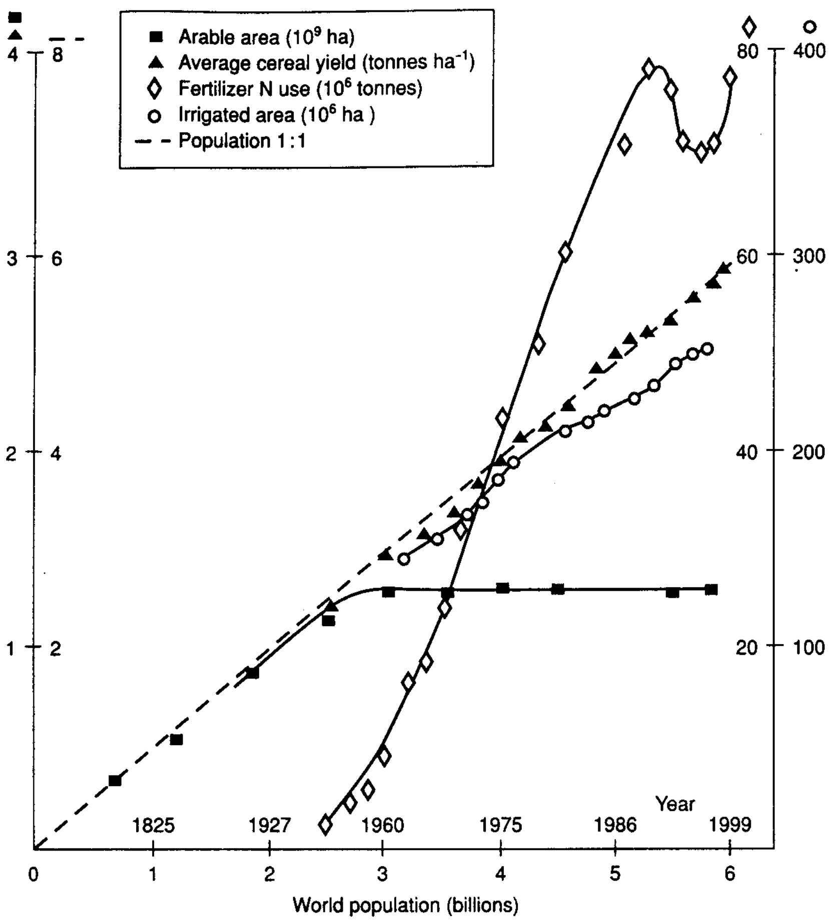

Figure 3.3
Relation between world population and arable area, average cereal yield, nitrogen fertilizer use, and irrigated area. Data from FAO Production Yearbooks. Source: Evans 1998, his figure 32, 205. Reproduced with the permission of Cambridge University Press.

land (figure 3.3). With a population of 3 billion or less, self-sufficient traditional agriculture could feed everyone, for example, with 2 billion hectares under cultivation, half of it yielding one ton per hectare of grain. Once world population passed 3 billion, self-sufficient traditional culture became impossible and intensification (extracting higher yields per hectare) became unavoidable (Evans 1998, 217). The area of arable land abruptly leveled off around 1.3 or 1.4 billion hectares. Although the total arable area has remained steady, the land cultivated now is not entirely the same land that was cultivated in 1960: some has been withdrawn from cultivation (as a result of urbanization and agricultural or industrial degradation) and new land of equal area has been recruited from natural ecosystems. Beyond 3 billion people, global average cereal yields have increased in close proportion to population size, at a steady ratio of one metric ton per hectare for each additional 2 billion people. After the invention of the Haber-Bosch process for nitrogen fixation, the production of artificial nitrogenous fertilizers increased much more rapidly than population. After 1960, a variety of factors combined to raise cereal yields and to revolutionize the relationship between population and the land. These factors included chemical fertilizers, pesticides (invented in the years before, during, and after World War II), massive extensions of irrigation, and new cultivars of rice, wheat, and maize (Harrar 1970). The new cultivars had higher crop planting density made possible by changed plant architecture. Multiple cropping, better farm management, and new institutions for providing farmers with credit, information, and other farm inputs also contributed to increased yields (Cohen and Fedoroff 1999).

A brief, incomplete list of some of the major inventions of the twentieth century that probably affected demographic variables (table 3.2) shows how difficult it would have been to predict these influences on the course of population. The miracle varieties of rice, wheat, and maize that feed billions today depend on the rediscoveries in 1900 of the work of Mendel and the subsequent development of cytogenetics and molecular genetics, as well as on the development of mathematical statistics by Ronald A. Fisher and others at agricultural research stations in the first half of the century. Inventions of domestic appliances like the electric washer, the electric vacuum cleaner, and the automatic toaster reduced the time required for domestic labor, freeing homemakers for economic activity and increasing the opportunity cost of raising children. The invention of the radio, television, and other forms of telecommunication facilitated the diffusion of ideas concerning small families and social, economic, and political modernization. The synthesis of quinine, other antimalarials, vaccines, and antibiotics, and the invention of other cheap public health interventions made possible dramatic reductions in childhood mortality in developing countries after World War II. The consequences of sexual activity were changed by new ways to diagnose and treat syphilis and other sexually transmitted diseases, and by a variety

Table 3.2
Inventions and innovations during the twentieth century that affected demographic variables directly or indirectly.

Year	Innovation	Putative demographic effect	Source
1900	Correns, De Vries and von Tschermak discover 1866 paper of Mendel, leading to modern genetics	Foundation of scientific breeding of plants and animals	Evans 1998, p. 102
1901, 1907, 1918	Fisher invents electric washer, Spangler invents electric vacuum cleaner, Strite invents automatic toaster	Reduced domestic labor required, usually of women	Hoffman 1987, pp. 157–160
1901, 1916	Taylor, White invent high-speed steel alloy, Brearley invents stainless steel	Facilitated mechanization of agriculture, household appliances, scientific instruments	Hoffman 1987, pp. 157–160
1902, 1905, 1906	Marconi invents radio magnetic detector, Fleming invents radio tube diode, De Forest invents radio amplifier and radio tube triode	Facilitated diffusion of ideas of social, economic, and political modernization and of small families	Hoffman 1987, pp. 157–160
1903	Wright brothers invent heavier-than-air flight	Facilitated mobility of people and goods, promoted global economic integration, undermined manpower as basis of military power	Hoffman 1987, pp. 157–160
1906, 1910	August von Wassermann discovers test for syphilis; Ehrlich discovers Salvarsan (606) for syphilis treatment	Enhanced surveillance and clinical treatment of problems in reproductive health	Hoffman 1987, pp. 157–160
1907, 1917	Benjamin Holt invents first gasoline tractor with tracks; Henry Ford introduces Fordson tractor	Mechanized agriculture displaced horses and increased productivity of farm workers	Evans 1998, p. 119
1908, 1930	Haber–Bosch process discovered for catalytic combination of nitrogen and hydrogen to produce artificial ammonia; anhydrous ammonia first applied directly to soil	Basis of the modern nitrogenous fertilizer industry; made possible yield increases	Evans 1998, p. 120
1911	Kettering invents automobile self-starter	Step toward mechanization of transport and traction, increased mobility	Hoffman 1987, pp. 157–160
1912, 1913, 1916, 1922	Holst, Froelich discover vitamin C; McCollum, Davis discover vitamin A; McCollum discovers vitamin B, then vitamin D	Facilitated improvements in nutrition and survival	Hoffman 1987, pp. 157–160
1913, 1922, 1930	Burton invents cracked gasoline, Midgley invents lead ethyl gasoline, Ipatieff invents high octane gasoline	Increased productivity of farm workers, promoted urbanization and mobility, lowering fertility	Hoffman 1987, pp. 157–160
1913, 1918	Julien Tournois discovers that long nights initiate precocious flowering in hops and hemp; H. A. Allard and W. W. Garner, U.S. Department of Agriculture, discover that length of night controls flowering in tobacco and soybeans	Foundation for spread of plant varieties from tropics to higher latitudes and vice versa	Evans 1998, pp. 102–103
1917	Jones invents hybrid corn	Step toward increased crop yields, better nutrition and better survival	Hoffman 1987, pp. 157–160
1918	Dempster invents mass spectroscope	Crucial tool for analytical chemistry in industrial and biomedical research	Hoffman 1987, pp. 157–160

Table 3.2 (continued)

Year	Innovation	Putative demographic effect	Source
1918	Rabe synthesizes quinine	Eased control of malaria	Hoffman 1987, pp. 157–160
1927	Farnsworth invents electronic television	Facilitated diffusion of ideas of social, economic, and political modernization and of small families	Hoffman 1987, pp. 157–160
1927	Warner Brothers invent talking movies	Facilitated diffusion of ideas of social, economic, and political modernization and of small families	Hoffman 1987, pp. 157–160
1928	Morkrum, Kleinschmidt invent teletype	Facilitated diffusion of ideas	Hoffman 1987, pp. 157–160
1929, 1941	Fleming discovers penicillin, Florey and Chain discover practical use	Improved survival of children and adults	Hoffman 1987, pp. 157–160
1930	Midgely et al. invent low-boiling fluorine compound refrigerants	Improved preservation of foods and medicines, improving survival	Hoffman 1987, pp. 157–160
1931	Knoll, Ruska invent electron microscope	Crucial analytical tool ~~for chemistry~~ in industrial and biomedical research	Hoffman 1987, pp. 157–160
1934, 1945, 1948	Domagk discovers sulfanilamide; Waksman discovers streptomycin; Duggar discovers aureomycin	Massively reduced mortality from microbial infections	Hoffman 1987, pp. 157–160
1939	Paul Mueller synthesizes DDT (dichlorodiphenyltricholorethane, first discovered in 1874 by Zeidler) as insecticide for J. R. Geigy AG of Basel	Rapidly produced by Allies to control typhus in Italy and the Rhine, malaria in Southeast Asia; also used to reduce insect pests of crops	Hoffman 1987, pp. 157–160
1941	Simple synthesis invented for substituted phenoxyacetic acids, such as plant hormone 2,4-D (2,4-dichlorophenoxy-acetic acid), and groups in United States and United Kingdom independently suggest their use as selective weed killers for cereal crops	Increased yields of cereal crops, simplified crop rotations, reduced energy used to grow crops, opened possibility of reduced tillage	Evans 1998, p. 127
1944	Howard Aiken et al. invent automatic sequence computer	Changed ability to assemble and analyze demographic data, facilitated revolution in global communication	Hoffman 1987, pp. 157–160
1944	Bretton Woods agreement initiates post–World War II system of international trade	Led to unprecedented rise in global prosperity	Schild 1995
1945	Food and Agricultural Organization of the United Nations established	Drew international attention to present and prospective problems in national and world food supply, engaging attention of public and national governments to food-population balance	www.fao.org
1945–1953	25 synthetic organic pesticides introduced, including chlordane, toxaphene, aldrin, dieldrin, endrin, heptachlor, parathion	Improved food production and had significant environmental and health effects	Hoffman 1987, pp. 157–160
1947	Shockley, Brattain, Bardeen invent transistor	Basis of microelectronics revolution in telecommunications and computing	Hoffman 1987, pp. 157–160
1948	United Nations proclaims Universal Declaration of Human Rights	Promoted modernization, including rights of women	Evans 1998, p. 115

Table 3.2 (continued)

Year	Innovation	Putative demographic effect	Source
1951	Watson and Crick discover structure of DNA	Foundation of modern molecular genetics	Hoffman 1987, pp. 157–160
1951	Carl Djerassi directs synthesis of cortisone at Syntex laboratory, leading to synthesis of progesterone and orally active inhibitor of ovulation	Enlarged range of contraceptive choice	Djerassi 1981, pp. 240–244
1952	Population Council established	Supported research in social sciences and biomedicine to improve family planning effectiveness	www.popcouncil.org
1952	Hoffman-La-Roche and Domagk discover isoniazid for tuberculosis	Potential to reduce TB mortality	Hoffman 1987, pp. 157–160
1952	McGuire discovers erythromycin	Improved survival	Hoffman 1987, pp. 157–160
1953, 1954, 1955	Salk develops polio vaccine; Enders and Peebles develop measles vaccine; Sabin develops oral polio vaccine	Massively reduced mortality and morbidity from viral infections	Hoffman 1987, pp. 157–160
1957	Russians launch Sputnik, beginning use of Earth-orbiting satellites for human purposes	Led to global observations of human impact on Earth, facilitated diffusion of ideas	Hoffman 1987, pp. 497
1960	FDA approves birth control pill invented by Gregory Pincus and John Rock, marketed as Enovid	Enlarged range of contraceptive choice	Djerassi 1981, p. 253
1960, 1966	Rockefeller and Ford Foundations found International Rice Research Institute (IRRI), Philippines; and International Centre for Maize and Wheat Improvement (CIMMYT), Mexico	Started crucial institutions for development and propagation of the Green Revolution	Evans 1998, p. 148
1961, 1962	Jack Lippes develops plastic intrauterine contraceptive device, marketed in following year	Enlarged range of contraceptive choice	Diczfalusy 1997
1962, 1966	Norman Borlaug releases first Mexican dwarf wheat; International Rice Research Institute releases IR8 variety of dwarf rice, the first lodging-resistant, fertilizer-responsive rice for the tropics —both key players in the Green Revolution (term in use by 1968)	Improved yields, increasing aggregate production without expansion of cultivated land	Evans 1998, pp. 134, 138
1965	First regeneration of whole plants (tobacco) from single cells	Opened applications of plant cell culture to crop modification	Evans 1998, p. 130
1967, 1977, 1979	Smallpox eradication campaign is launched, last naturally occurring case of smallpox is reported, smallpox is eradicated	Controlled a major cause of human sickness and death in past centuries	http://Whqsabin.who.int:8082/smallpox.htm
1969, 1970, 1972	Photographs of Earth from Moon; Earth Day in United States; United Nations Conference on the Human Environment held in Stockholm and *Limits to Growth* published	Changed perceptions of human situation on Earth	Evans 1998, p. 133; Meadows et al. 1972

Table 3.2 (continued)

Year	Innovation	Putative demographic effect	Source
1971	Consultative Group on International Agricultural Research established to support international agricultural research centers in partnership with developing countries	Contributed to increased food production	Evans 1998, p. 134
Late 1970s, early 1980s	Epidemic of AIDS started in sub-Saharan Africa, Latin America, Caribbean, Western Europe, North America, Australia, New Zealand	Beginning of a global epidemic with massive consequences for mortality	United Nations Population Fund 1997, p. 7
1983	Ni is shown to be essential trace element for plant growth (part of a series of discoveries of essential trace elements over a century)	Made possible crop growth in deficient soils	Evans 1998, p. 105
1984	Functional antibiotic resistance gene is transferred from bacterium to tobacco	First reported transgenic plant began plant biotechnology revolution	Evans 1998, p. 162
1996	Genome sequence of budding yeast *Saccharomyces cerevisiae* published	First complete eukaryotic genome sequence	C. elegans Sequencing Consortium 1998
1998	Genome sequence (97 million bases) of nematode worm *Caenorhabditis elegans* reported	First genome sequence of a multicellular organism, of direct relevance to control of nematode parasites, and indirect relevance to control of all human diseases	C. elegans Sequencing Consortium 1998, p. 2012

References

C. Elegans Sequencing Consortium. 1998. "Genome Sequence of the Nematode *C. elegans*: A Platform for Investigating Biology," *Science* 282: 2012–2018, 11 December.

Diczfalusy, Egon. 1997. *The Contraceptive Revolution: An Era of Scientific and Social Development*. New York: Parthenon.

Djerassi, Carl. 1981. *The Politics of Contraception: Birth Control in the Year 2001*. San Francisco: W. H. Freeman.

Evans, Lloyd T. 1998. *Feeding the Ten Billion: Plants and Population Growth*. Cambridge and New York: Cambridge University Press.

Hoffman, Mark S. ed. 1987. *World Almanac and Book of Facts 1988*. New York: World Almanac, 157–160.

Meadows, Donella H., Dennis L. Meadows, Jírgen Randers, and William W. Behrens III. 1972. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. New York: Signet, New American Library. 2d edition, 1974.

Schild, Georg. 1995. *Bretton Woods and Dumbarton Oaks: American Economic and Political Postwar Planning in the Summer of 1944*. New York: St. Martin's Press.

United Nations Population Fund. 1997. *AIDS Update 1997: A Report on UNFPA Support for HIV/AIDS Prevention*. New York: UNFPA.

of new contraceptives. Institutional innovation also played a major role in many fields with demographic impact, for example, in developing and promoting family planning (Population Council, founded in 1952), in agricultural innovation (Consultative Group on International Agricultural Research, founded in 1971), and in international trade (Bretton Woods agreement, concluded in 1944). To the extent that these inventions and innovations were unpredictable, one must expect similar surprises in the coming century. One must even allow for the possibility that the nature of the coming surprises will be unexpected.

In summary, population projections are uncertain because the initial data may be erroneous; the rates of birth, death, and migration in cohort-component models may be projected erroneously; external factors may change unexpectedly in exogenous projections; external factors may change as expected but the relationship between those factors and demographic rates may change; policies and programs may develop to influence the rates of birth, death, and migration; and feedbacks from anticipated population change may intervene to alter further population change in unanticipated ways. The social sciences have little ability to predict the aggregate course of the fundamental demographic processes of birth, death, and migration.

For a longer-term perspective, qualitative scenarios of the future are likely to be at least as interesting as detailed quantitative projections, provided the scenarios offer no false promises of reliability. Bellamy (1888, 1982) offered no explicit demographic projections, but his scenario of what life might be in the year 2000 remains full of interest.

A Speculative Scenario of the Twenty-First Century

Speculations about the future of population, environment, economics, and culture are not intended to divert attention from today's serious problems—the poverty, malnutrition, illiteracy, disease, and indignity of life for billions of people, plus unprecedented physical, chemical, and biological perturbations of the planet. These speculations aim to envision a positive future worth working toward. The future is at least partially an object of choice, and not entirely an inevitable outcome of an uncontrollable mechanical world.

I shall assume that the next century will not be afflicted by a lethal global pandemic of a novel infectious disease, by massively destructive warfare, or by a meteoric impact that darkens the skies for years. I assume

no abrupt shift in ocean circulation and global climate that melts all polar ice, raises sea level by tens of meters, and ends conventional agriculture. All of these catastrophes are conceivable. None is especially unlikely. I exclude such possibilities because I have nothing useful to say about what would follow.

Population and Society

For the next quarter- to half-century, one can make four statements about the future of global population with fair confidence. First, the population will be bigger than it is now. Second, the population will increase less rapidly, absolutely and relatively, than it has recently. Third, the population will be more urban than it is now. Fourth, the population will be older than it is now.

Here are some details on each of these four points.

First, the twenty-first century is unlikely to see a reversal of world population growth for several decades at least. More young people are entering their childbearing years now than ever before in history. The 1998 long-term *low*-fertility projection of the United Nations estimated that global population will peak near 7.7 billion in the middle of the twenty-first century, and will fall to 5.6 billion by 2100. The world previously had 5.6 billion people around 1993. Unless future population growth is much lower than anticipated in the United Nations' low projection, the twenty-first century will have billions more people than the twentieth century.

Second, in the twentieth century, world population increased 3.8-fold. World population is very unlikely to increase 3.8-fold in the twenty-first century. At the end of the twentieth century, after 35 years of slowing population growth, a continued slowing of population growth in the twenty-first century seems very likely. Some demographers believe that another doubling of the earth's population is unlikely ever to occur (Lutz et al. 1997). If the rate of increase of population continues to fall, then the twentieth century was and will be the only century in the history of humanity to see a doubling of the earth's population within a single lifetime. Human numbers will probably never again nearly quadruple within a century. (But remember the baby boom! Surprises happen.)

Third, in Europe, the rush of people from the countryside to cities dates back to the eleventh century. Urbanization has occurred worldwide for at least two centuries. At the end of the twentieth century, there were perhaps 20 cities of 10 million people or more and 47 percent of all people lived in cities (I add the qualifier "perhaps" because of variations among countries' definitions of who is included in a major city and because of uncertainty in data on where people live). During 1990–1995, the world's urban population grew by 2.4 percent per year, 3 times as fast as rural populations grew (0.7 percent per year). The twenty-first century is unlikely to see a reversal in the relative growth of urban population. In its 1996 estimate of world urbanization prospects, the United Nations Population Division (1997b) estimated that almost all population growth in the next half-century will be located in cities, while the rural population of the world will remain nearly constant around 3 billion people. The U.N. Population Division (1997a) estimated that 61.1 percent of world population would live in urban areas by 2030 (83.7 percent in more developed regions, 57.3 percent in less developed regions). By 2030, the urban population would total 5.1 billion, 1.0 billion in the more developed regions and 4.1 billion in the less developed regions. If urbanization occurs as anticipated, then the twentieth century was and will be the last century in human history in which most people live in rural areas. In the next century, humanity will be predominantly urban. Of course, figures on urbanization disguise ambiguities and variations between countries in definitions of "cities" and "urban." While the numbers should not be taken too literally, the trend toward urbanization is clear.

Fourth, the twentieth century saw the world fraction of children aged 0–4 years gradually decline, and the world fraction of older people aged 60 years or more gradually increase. Both percentages met at 10 percent in the year 2000. This trend results from improved survival and reduced fertility. Improved survival raised the world's expectation of life from perhaps 30 years at the beginning of the twentieth century to more than 66 years at the beginning of the twenty-first century. Reduced fertility rates added smaller cohorts to the younger age groups. The twenty-first century is unlikely to see a reversal in the aging of world population. In its 1998 medium-variant projection, the United Nations estimated that by the middle of the twenty-first century, the fraction of the population aged 0–4 years will fall from 10 percent to less than 7 percent, while the fraction of the population aged 60 years or more will rise from 10 percent to more than 22 percent. In this projection, the ratio of older people to young children is expected to rise from 1-to-1 now to 3.3-to-1 in half a century. In all the variant projections developed by the United Nations, the ratio of elderly to young children is expected to grow. The lower future fertility, the higher the ratio of elderly people to young children. If the future resembles any of the U.N. projections, then the twentieth century was and will be the last century in human history to see younger people outnumber older people. The next century will be a world of predominantly older people. Among the elderly, women will outnumber men by as much as 2 to 1. New social arrangements among the elderly will arise.

For the very long-term future, one can make three statements about the future of global population with great confidence (Cohen 1995, 153–157). First, the future of human population growth is uncertain. Is the population of the world in the year 2200 likely to be closer to 2 billion or 15 billion people? No one knows. If different regions of the world have differing levels of fertility in 2200, where will the regions of high and low fertility be? No one knows. Second, in the long run, global population growth rates must necessarily be very close to 0 (though the same constraint need not apply to any sufficiently small region of the world). Global population has grown roughly 1,000-fold in the last 10,000 years, giving an average growth rate of 0.07 percent per year. It seems highly unlikely that Earth will shelter 6 trillion people 10,000 years in the future, hence the population must grow by much less than 0.07 percent per year on average over the next ten millennia. Third, in a stationary population, the average length of life equals 1 divided by the birth rate. Since global population must eventually become stationary on the average over time, people will eventually have to choose between having long lives on the average and having a high birth rate. At the global level, there is no way to have both.

The United Nations Population Division (1998) prepared official projections of future population sizes using the cohort-component method (figure 3.4). It is possible to obtain remarkably similar results by very rough calculations, at least for the year 2050. In 1999, the global population of 6 billion was increasing by almost 80 million people per year. Were growth to continue at this annual rate of 1.4 percent, the population size would double to 12 billion in roughly 50 years. Most demographers view this scenario as unlikely because the rate of increase in population size has been declining since 1965 and the absolute number of people added annually to the global population has been dropping since 1990.

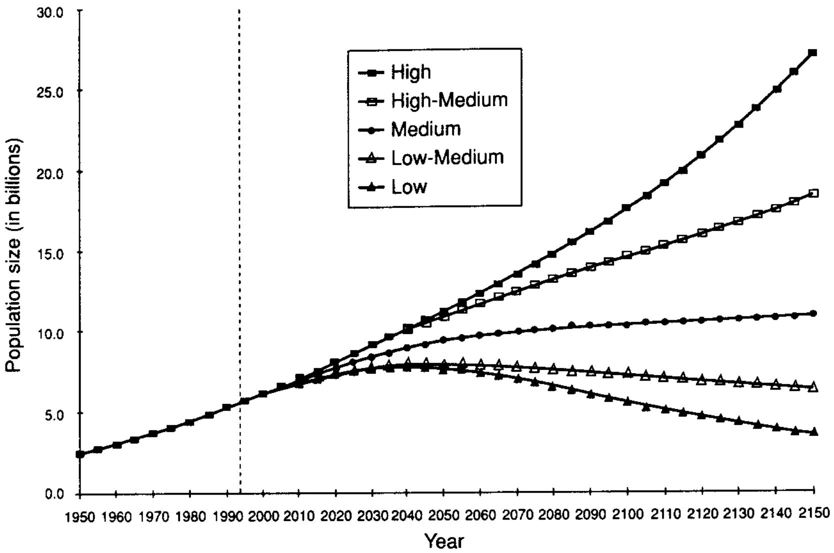

Figure 3.4
World population projections according to five main fertility scenarios of the United Nations Population Division (1998b, their figure 4, 20). Values to the right of the vertical dotted line are projected. Reprinted by permission.

If the annual increase in population were to drop linearly from today's 80 million to zero over 50 years, then the average annual increase would be 40 million per year for 50 years. Population would increase by 2 billion people to give a population size of 8 billion in the year 2050. This scenario requires accelerating declines in fertility in presently poor countries with high fertility rates.

Between the extremes of a constant relative growth rate and a rapid decline to no population growth at all, it is plausible to imagine a population size in 2050 of 9 billion or 10 billion (United Nations Population Division 1998a, b). There are few objective grounds for confidence about the future trajectory of human fertility in the coming century. Remembering that the human population numbered only 3 billion as recently as 1960, population sizes of 8 billion or 12 billion can only be viewed with awe.

In 1998, roughly 1.2 billion people—1 person in 5—lived in the developed countries, defined as North America north of the Rio Grande, Europe, Japan, Australia, and New Zealand, and sometimes including

some smaller Asian countries. According to 1998 estimates (Population Reference Bureau 1998), the TFR of 1.2 billion people in the more developed regions was 1.6 children per woman, well below the replacement level of 2.1 children per woman. Little if any of the next half-century's population growth is expected to occur in these countries.

By contrast, the 3.5 billion people in the less developed regions outside China had a TFR of 3.8 children per woman and a doubling time of 35 years, at the end of the twentieth century. Unless the pace of economic and educational development accelerates markedly, the fraction of people living in developing countries will increase from 80 percent at the end of the twentieth century to 90 percent by 2050. The population density in the developed countries is currently about 22 people/km^2, while that in the developing countries is roughly 55 people/km^2. The latter number will roughly double to 100 people/km^2 if global population grows to 10 billion, largely as a result of increases in the developing countries. This is one person per hectare. Attaining acceptable qualities of life in developing countries at such population densities will be a challenge. The challenge has not been met even at today's population densities.

If the whole world had the level of fertility of the more developed regions today, world population would peak in the middle of the twenty-first century and then gradually decline. On the other hand, if fertility remained at its present high level in the less developed regions outside China, rapid population growth would continue, even without a resurgence of fertility elsewhere. In this case, another quadrupling of the Earth's total population in the coming century could result from three doublings (at 35 years each) of the population of the less developed regions outside China. While such growth cannot be precluded demographically, other factors might make such growth extremely difficult or impossible.

A century from now, humankind will live in a global garden, whether it be well or poorly tended (Cohen 1998, Janzen 1998). Most people will live in cities, surrounded by large, thinly populated zones for nature, agriculture, and silviculture. Worldwide, between 100 and 1,000 cities of 5 million to 25 million people each will serve their inhabitants' wants for food, water, energy, waste removal, political autonomy, and cultural and natural amenities. Some cities will serve people who want to live only with people ethnically and culturally like themselves. Other cities will serve people who are attracted by ethnic and cultural diversity. Different cities will gain shifting reputations as being favorable for young people, child-rearing, working, or retirement. The efficiency and quality of services that cities provide will depend on the quality of their management and on the behavioral skills and manners of their populations.

Just as feudal obligations were replaced by labor markets, other present rights and obligations will increasingly be replaced by markets. For example, there could be a worldwide market in permits for permanent residence in cities. The prices of these permits could be tacked on real estate or rental prices. City managements will compete to command market rewards for the public goods they are able to provide. Countries like the United States that insist on a person's right to leave his or her country of birth will have to decide if that implies a person's right to enter some other country.

Social and individual values will determine how far markets will be allowed to intrude into allocations previously determined by traditional means. Women around the world will demand and receive education and jobs comparable to men's education and jobs. Women will, therefore, have increased autonomy and power in the family, economy, and society. Partly as a consequence of women having attractive alternatives to childbearing and child-rearing, the number of children that women bear in a lifetime will most likely decline globally to the replacement level or below. As childbearing will occupy a falling fraction of most women's lengthening lives, women will intensify their demands for other meaningful roles. If the nuclear family of married adults and minor children comes to occupy a transient interval of a prolonged life cycle, the consequent reduction in average household size and composition could have substantial effects economically, environmentally, and culturally.

Though global human population growth could well end in the next century, some regions will be net exporters of people while others will be net importers. Rising pressures for migration from poorer to richer countries will strain traditionally xenophobic countries like Germany and Japan, as well as traditionally receptive countries like the United States, Australia, Sweden, and Argentina. Migrations will bring culturally diverse populations into increasing contact. The result will be many frictions as humans learn manners and tolerance. Intermarriages will make a kaleidoscope of skin colors.

Environment

A major challenge of the coming century will be coping with the environmental impacts of agricultural intensification. These impacts are partly physical (changes in the quality of soil after prolonged cultivation), partly chemical (effects of fertilizers and biocides beyond their intended targets, effects of methane and nitrogenous animal wastes), and partly biological (genetic, ecological, and epidemiological). If the 3 billion people in the rural areas of developing countries over the next half-century have to provide food and fiber to an enormously increased number of urban people in developing countries, it will be a challenge to do so without poisoning themselves and their environment, in the face of unpredictable climatic constraints (Evans 1998). Alternatives will be to acquire agricultural products from the developed world by trade or gift or to promote agricultural production within urban regions of developing countries.

Today's simplified agricultural ecosystems will be replaced by managed ecosystems of high complexity. Biological controls and farmer intelligence will aim to maximize yields while reducing biocidal inputs like today's pesticides and herbicides. Required agricultural inputs of nutrients and energy will be derived from human, animal, and industrial wastes rather than from today's fertilizers and fossil fuels. Unwanted effluents like eroded soil or agricultural runoff with pesticides and fertilizers will be eliminated or converted to productive inputs for industrial and urban use. Providing the farmer skills and supportive institutions required for such sophisticated agricultural management will be another major challenge.

Continental shelves, especially off Asia, will be further developed to provide food, energy, and perhaps living space. Oceanic food sources will be largely domesticated. The capture of any remaining wild marine animals will be managed like deer hunting now. The tropical forests that survive the onslaught of population growth and economic exploitation between 1950 and 2050 will be preserved as educational and touristic curiosities, like the immensely popular John Muir Woods north of San Francisco. Many forests will be meticulously managed for fiber, food, pharmaceuticals, and fun (that is, recreational exploration).

The atmosphere will also be managed. Rights to add carbon dioxide, methane, and other climatically significant trace gases and particles to the atmosphere will be traded in global markets for the services that natural ecosystems provide. Governments will recognize the potential of atmospheric and many other natural ecosystem services (Daily 1997) to generate taxes that can support other public goods. Gases will be manipulated as part of food production and wildlife management. For example, genetically engineered bacteria and farming practices will manipulate agricultural methane production.

People will revalue living nature as they realize that they do not know how to multiply old forests, coral reefs, and the diversity of living forms. People will increasingly value nature's genetic resources and aesthetic amenities. Conservation movements will gain renewed strength in collaborations with businesses.

The intensive management of continents, oceans, and the atmosphere will require massive improvements in data collection and analysis, and especially in concepts. A century hence, we will live on a wired Earth. Continents, air, and sea will be continuously sensed. Like the weather stations on land and the satellites that now monitor the atmosphere, the oceans and solid earth crust of the next century will have three-dimensional lattices of sensing stations at all depths. Mathematical models of earth, air, and sea will aim to predict major events such as El Niños, hurricanes, earthquakes, volcanoes, major plumes of hot water from oceanic vents, and shifts in major ocean currents. These models will improve with at least million-fold improvements in computing power over the next century. Models will integrate not only the atmosphere, crust, and oceans, but also human and other biological populations including domestic animals, trees, cereal crops, and infectious diseases; economic stocks and flows, including all natural resources; informational stocks and flows, including scientific, literary, artistic, and folk traditions; and familial, social, institutional, and political resources and constraints. Comprehensive models will include factors beyond human control, such as solar flares, and will represent, though not predict, human decisions.

In spite of improvements in information, concepts, and management, the Earth will still bring surprises. Geophysical surprises will arise from an improved awareness of what the planet is doing, from inherent instabilities in geophysical systems described by the mathematics of chaos, and from rising human impacts. Surprising infectious diseases will continue to emerge from the infinite well of genetic variability. Historically, each factor-of-10 increase in the density of human settlements has made possible the survival of new human infections (Anderson and May 1991). Unless the sanitary infrastructure of the next century's megacities improves dramatically, large cities could become incubators for new infectious diseases. As more humans contact the viruses and other pathogens of previously remote forests and grasslands, dense urban populations and global travel will increase opportunities for infections to spread. However, people know far more now than in the past about how to prevent and contain the spread of infection. The ability to apply this knowledge depends on future political and social organization.

Economies

A slowing, cessation, or reversal of population growth need not entail a slowing or reduction in economic growth (Kosai, Saito, and Yashiro 1998). In the near-term, roughly a 4-fold increase in aggregate economic output will be required to bring the four-fifths of humanity living on a few thousand dollars a year up to the level of the one-fifth of humans living on roughly twenty thousand dollars a year. If poverty is eliminated from the Earth, the demand for positional goods (Hirsch 1976) should continue or be intensified, although environmental constraints may require those goods to take informational or symbolic form. As art dealers know, there is apparently no limit to the value that can be attached to rare beauty.

Economies will be increasingly integrated. Cities will concentrate the talent and resources required for international business. Hardly any complex product will be conceived, financed, engineered, manufactured, sold, used, and retired within the boundaries of a single political unit. Businesses will learn to profit from the eternity of atoms by designing products for use, return, and regeneration. Governments will find that a growing fraction of the power to control the economic well-being of their citizens lies outside their borders. Economic integration will give profit to those who can recognize the comparative advantage of other societies.

Information will become increasingly valuable. Those who can create it, analyze it, and manage effectively on the basis of it will be at a premium. Information technology and global economic integration will grow hand in hand. The definition of wealth may change toward one that is more information-rich and less material-intensive.

As the peoples of Asia, Latin America, and Africa grow wealthier (too slowly, and with too many major setbacks), their environmental fatalism and modest demands for food will be replaced by impatience with the accidents of nature, intolerance of environmental mismanagement, and refusal to eat less well than their neighbors. The need for careful global management, trusteeship, or stewardship will become irresistible—particularly stewardship of living resources, human and nonhuman.

Culture

Culture pervades everything that can be said about population, the environment, and economies. For example, culture conditions the productive and reproductive roles of men and women; defines which biological raw materials are seen as food and which are not; and shapes what consumers demand from the economy, including the balance of informational and material products.

An international common law—not a world government but rather international standards of behavior—will grow stronger and more comprehensive in a progression from technical, to commercial, to political law. International agreements on vaccination and on metric measures work because they benefit all who abide by them, and many who do not. Growing investments by multinational corporations will force the development of international contract law. Once the regional and global economic customs, institutions, and laws are firm, it will become too costly for nation-states or their successors to ignore them. Legal and economic resolutions of political conflicts will become more efficient than violent ones. Not all parts of the world will learn this lesson with equal ease.

A slowing or reversal in the growth of the human population in the twenty-first century could portend a more rapid spread of the three elements of citizenship identified by Marshall (1949). To understand why, it is useful to review the experience of Europe in the fourteenth and fifteenth centuries. This experience is one of the few documented examples of how societies responded to widespread—not merely local—population decline. Waves of the Black Death, probably related to today's bubonic plague, together with pervasive violence permitted or instigated by poor and sometimes malicious governments, killed from one-third (Cipolla 1993) to two-thirds (Herlihy 1997) of the European population. North and Thomas (1973) and Herlihy (1997) argued that this catastrophe shook Europe loose from a stable equilibrium of high population density, intensive grain production, and widespread poverty. Before the Black Death, admission to guilds had been hereditary or strictly limited. A scarcity of workers following the drop in population forced guilds to recruit more widely from among the poor. Parents shifted much of their bequests from pietistic charity to their children. Increased lands per person shifted diets toward more meat, the food of the rich previously. The scarcity of people raised the wages of both agricultural and urban laborers and stimulated the development of labor-saving technology. From an oversimplified economic perspective, when the supply of people dropped, the price of people rose. A dramatic fall in the abundance of people was followed by an increase in their value.

Cipolla (1993) argued that key factors in the development of Europe were the rise of urban society in the eleventh to thirteenth centuries, in which professionals had a prominent place, and the technological innovations in both agriculture and manufacturing that came with urbanization of the population. According to Cipolla, the Black Death saved these gains from being eaten up, as they were in Asia, by the rise of population.

However, numbers of people cannot be the whole story. If the decimation of the Amerindians following the European conquests raised the price of people in the New World, it led Europeans to tighten their control of the subjugated populations. This example shows that the effects on well-being of a major drop in population depend as much on the relations of power in a society as on numbers. To judge by the preventable ills of the human population today, people are collectively valued cheaply. Three-quarters of a billion people are chronically undernourished; at least another billion are malnourished; a billion adults are illiterate; perhaps 2 billion people are infected with the bacillus of tuberculosis (with hundreds of millions more under threat from other infectious diseases); and roughly four-fifths of the world's population lives on average annual incomes of at most a few thousand dollars.

The transition from a doubling of population in the last 40 years of the twentieth century to a possible absolute decline in the twenty-first century could be accompanied by a rise in the value of people, other things being equal. A perceived slowing in population growth could raise the incentives to nurture well those who are born. It could speed the worldwide diffusion of the civil, political, and social elements of good citizenship. When it can no longer be assumed that there will be plenty more people to come, then assuring that people have food, education, health, and a meaningful civic life may take on greater urgency. But as the example of the Amerindians shows, this positive outcome is by no means inevitable. If major changes for the better do occur, it will be to the lasting credit of humans that, this time, the demographic and social changes were in large part brought about or at least facilitated by the reproductive choices of individuals.

Geophysical and biological surprises, the revaluation of living nature, our greater dependence on people all over the world, our growing determination to act lawfully, and our own aging (individually and as a population) could increasingly inspire in many people a greater awe for the world, for others, and for ourselves.

Other Scenarios Are Possible

There is no shortage of scenarios for the future of population (Lutz 1994, 1996; United Nations 1997a, b; 1998a, b) or for the future of the entire world (McRae 1994, Coates et al. 1997, Ocko 1997, Bossel 1998, Hammond 1998). Bossel (1998) developed two scenarios, one called "competition" and the other called "partnership." For each scenario, he examined infrastructure, the economic system, the social system, individual development, government, environment, resources, and the future. The goals of his agenda for change included indicators for sustainable development, efficient technologies, education and information, the regionalization of economic activities, population control, the equitable distribution of work, the rights of affected systems, and participatory democracy. Hammond (1998) developed three scenarios called "market world: a new golden age of prosperity?"; "fortress world: instability and violence?"; and "transformed world: changing the human endeavor?" More than Bossel, Hammond emphasized the very different challenges faced by different regions of the world.

Bossel, Hammond, and I share the conviction that the future is at least partially a matter of choice. Many, perhaps most, things in the future are intrinsically hidden from us now. Nevertheless, we constantly make choices about investing, or not investing, in the next generation of humans individually and institutionally; about protecting the other species that support our life and make the planet habitable; and about conserving the physical setting of continents, oceans, and atmosphere. We can foresee the consequences of our choices only dimly, but we can aspire to make choices that will improve our chances for a livable future.

Acknowledgments

I thank Sandra Waldman for helpful information, and Tim Besley, Chris Caswill, Richard Cooper, Paul David, Valerie Herr, Nathan Keyfitz, Jonathan Messerli, Richard O'Brien, Samuel Preston, Barney Rush, Peter Schwartz, and George Whitesides for helpful comments on earlier presentations and drafts of this material. I acknowledge with thanks the support of U.S. National Science Foundation grants BSR92–07293 and DEB 99–81552, and the hospitality of Mr. and Mrs. William T. Golden.

References

Ahlburg, Dennis A., and James W. Vaupel. 1990. "Alternative Projections of the U.S. Population." *Demography* 27(4): 639–652.

Anderson, R. M., and R. M. May. 1991. *Infectious Diseases of Humans: Dynamics and Control*. Oxford: Oxford University Press.

Ayres, Robert U., William H. Schlesinger, and Robert H. Socolow. 1994. "Human Impacts on the Carbon and Nitrogen Cycles." Pp. 121–155 in *Industrial Ecology and Global Change*. New York: Cambridge University Press.

Bellamy, Edward. 1888. *Looking Backward, 2000–1887*. Boston: Ticknor, 1888. Edited by Cecelia Tichi. Reprinted, 1982. Harmondsworth, Middlesex, England; New York: Penguin Books.

Berry, Brian J. L. 1990. "Urbanization." Pp. 103–119 in *The Earth as Transformed by Human Action*, ed. B. L. Turner et al. Cambridge: Cambridge University Press.

Bledsoe, Caroline H., John B. Casterline, Jennifer A. Johnson-Kuhn, John G. Haaga. eds. 1999. *Critical Perspectives on Schooling and Fertility in the Developing World*. Washington, D.C.: National Research Council, National Academy Press.

Bongaarts, John, and Rodolfo A. Bulatao, eds. 2000. *Beyond Six Billion: Forecasting the World's Population*. Panel on Population Projections, Committee on Population, Commission on Behavioral and Social Sciences and Education, National Research Council. Washington, D.C.: National Academy Press.

Bossel, Hartmut. 1998. *Earth at a Crossroads: Paths to a Sustainable Future*. Cambridge: Cambridge University Press.

Cannan, Edwin. 1895. "The Probability of a Cessation of the Growth of Population in England and Wales during the Next Century." *Economic Journal* 5, no. 20 (December): 505–515.

Chao, Benjamin Fong. 1995. "Anthropogenic Impact on Global Geodynamics due to Reservoir Water Impoundment." *Geophysical Research Letters* 22, no. 24 (15 December): 3529–3532.

Cipolla, Carlo M. 1993. *Before the Industrial Revolution: European Society and Economy, 1000–1700*, 3d ed. New York: W. W. Norton.

Coates, Joseph F., John B. Mahaffie, and Andy Hines. 1997. *2025: Scenarios of U.S. and Global Society Reshaped by Science and Technology*. Greensboro: Oakhill Press.

Cohen, Joel E. 1986. "Population Forecasts and Confidence Intervals for Sweden: a Comparison of Model-Based and Empirical Approaches." *Demography* 23, no. 1 (February): 105–126; 25, no. 2 (May 1988): 315.

———. 1995. *How Many People Can the Earth Support?* New York: W. W. Norton.

———. 1998. "A Global Garden in the Twenty-First Century?" *The Phi Beta Kappa Key Reporter* 63, no. 3 (Spring): 1–5.

———. 1999. "Should Population Projections Consider 'Limiting Factors'—and If So, How?" Pp. 118–138 in *Advances in Population Projections*, ed. W. Lutz, James W. Vaupel, and Dennis Ahlburg. Supplement to *Population and Development Review* 24.

Cohen, Joel E., and Nina V. Fedoroff, eds. 1999. *Colloquium on Plants and Population: Is There Time?* Washington, D.C.: National Academy Press.

Colclough, Christopher, and Keith Lewin. 1993. *Educating All the Children: Strategies for Primary Schooling in the South*. Oxford: Clarendon Press.

Crossette, Barbara. 1997. "How to Fix a Crowded World: Add People." *New York Times Week in Review*, 2 November, section 4, 1–3.

Daily, Gretchen C. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington, D.C.: Island Press.

Daly, Herman E., and J. B. Cobb. 1989. *For the Common Good: Redirecting the Economy toward Community, the Environment, and a Sustainable Future*. Boston: Beacon Press.

Eberstadt, Nicholas. 1997a. "The Population Implosion." *Wall Street Journal*, 16 October, section A, 22.

———. 1997b. "The Population Implosion." *The Public Interest*, Fall, 3–22.

Engelman, Robert, 1998. *Profiles in Carbon: An Update on Population, Consumption, and Carbon Dioxide Emissions*. Washington, D.C.: Population Action International.

Evans, Lloyd T. 1998. *Feeding the Ten Billion: Plants and Population Growth*. Cambridge: Cambridge University Press.

Gelbard, Alene, and Carl Haub. 1998. "Population 'Explosion' Not Over for Half the World." *Population Today* (Population Reference Bureau) 26(3): 1–2.

Hajnal, J. 1957. "Mathematical Models in Demography." *Cold Spring Harbor Symposia on Quantitative Biology* 22: 97–103.

Hammond, Allen. 1998. *Which World? Scenarios for the Twenty-First Century: Global Destinies, Regional Choices*. Washington, D.C.: Island Press.

Harrar, J. George. 1970. "Plant Pathology and World Food Problems." *Perspectives in Biology and Medicine* 13: 583–596.

Herlihy, David. 1997. *The Black Death and the Transformation of the West*, ed. Samuel K. Cohn, Jr. Cambridge: Harvard University Press.

Hirsch, Fred. 1976. *Social Limits to Growth*. Cambridge: Harvard University Press.

Holland, Elisabeth A., and Jean-Francois Lamarque. 1997. "Modeling Bioatmospheric Coupling of the Nitrogen Cycle through No_x Emissions and No_y Deposition." *Nutrient Cycling in Agroecosystems* 48: 7–24.

Janzen, Daniel H. 1998. "Gardenification of Wildland Nature and the Human Footprint." *Science* 279: 1312–1313.

Keilman, Nico. 1999. "How Accurate Are the United Nations World Population Projections?" Pp. 15–41 in *Frontiers of Population Forecasting*, ed. Wolfgang Lutz, James W. Vaupel, Dennis A. Ahlburg. Supplement to *Population and Development Review* 24. New York: Population Council.

Keyfitz, Nathan. 1993. "Increasing the Accuracy and Usefulness of the GDP." *Statistical Journal of United Nations Economic Commission for Europe* 10: 371–380.

Kosai, Y., J. Saito, and N. Yashiro. 1998. "Declining Population and Sustained Economic Growth: Can They Coexist?" *American Economic Review* 88(2): 412–416.

Laing, Jonathan R. 1997. "Baby Bust Ahead." *Barron's*, 8 December, 37–42.

Lutz, Wolfgang, ed. 1996. *The Future Population of the World: What Can We Assume Today?* London: Earthscan.

Lutz, Wolfgang, Warren C. Sanderson, and Sergei Scherbov. 1997. "Doubling of World Population Unlikely." *Nature* 387(6635): 803–805, 19 June.

Lutz, Wolfgang, James W. Vaupel, and Dennis A. Ahlburg, eds. 1999. *Frontiers of Population Forecasting*. Supplement to *Population and Development Review* 24. New York: Population Council.

Maddison, Angus. 1995. *Monitoring the World Economy 1820–1992*. Paris: Organisation for Economic Cooperation and Development.

Malthus, T. R. 1798, 1970. *An Essay on the Principle of Population*. Edited by A. Flew. London: Penguin.

Marshall, T. H. 1964. "Citizenship and Social Class." In *Class, Citizenship and Social Development*. New York: Doubleday and Co.

McRae, Hamish. 1994. *The World in 2020: Power, Culture, and Prosperity*. Boston: Harvard Business School Press.

North, Douglass C., and Robert Paul Thomas. 1973. *The Rise of the Western World: A New Economic History*. Cambridge: Cambridge University Press.

Ocko, Stephanie. 1997. *Doomsday Denied: A Survivor's Guide to the Twenty-First Century*. Golden: Fulcrum Publishing.

Office of Science and Technology Policy. Executive Office of the President. 1997. *Climate Change: State of Knowledge*. Washington, D.C.

Population Reference Bureau. 1998. *1998 World Population Data Sheet*. Washington, D.C.: Population Reference Bureau.

Postel, Sandra L., Gretchen C. Daily, and Paul R. Ehrlich. 1996. "Human Appropriation of Renewable Fresh Water." *Science* 271: 785–788.

Pritchett, Lant. 1995. "Divergence, Big Time." Policy Research Working Paper 1522. World Bank, Washington D.C.

Preston, S. H. 1976. *Mortality Patterns in National Populations: With Special Reference to Recorded Causes of Death*. New York: Academic Press.

Preston, S. H. 1995. "Human Mortality Throughout History and Prehistory." Pp. 30–35 in *The State of Humanity*, ed. Julian L. Simon. Cambridge, Mass.: Blackwell Publishers.

Raven, J. A. 1998. "Extrapolating Feedback Processes from the Present to the Past." *Philosophical Transactions of the Royal Society of London* B 353: 19–28.

Sanderson, Warren C. 1999. "Knowledge Can Improve Forecasts: A Review of Selected Socioeconomic Population Projections Models." Pp. 88–117 in *Frontiers of Population Forecasting*, ed. Wolfgang Lutz, James W. Vaupel, Dennis A. Ahlburg. Supplement to *Population and Development Review* 24. New York: Population Council.

Socolow, Robert, and Valerie Thomas. 1997. "The Industrial Ecology of Lead and Electric Vehicles." *Journal of Industrial Ecology* 1(1): 13–36.

Teitelbaum, Michael S., and Jay M. Winter. 1985. *The Fear of Population Decline*. Orlando: Academic Press.

United Nations. 1991. *The World's Women 1970–1990: Trends and Statistics*. Social Statistics and Indicators Series K, No. 8 ST/ESA/STAT/SER.K/8. New York: United Nations.

———. 1995. *Women in a Changing Global Economy: World Survey on the Role of Women in Development*. E.95.IV.1. New York: United Nations.

United Nations Development Programme. 1992. *Human Development Report 1992*. New York and Oxford: Oxford University Press.

United Nations Population Division. 1997a. *World Urbanization Prospects: The 1996 Revision, Estimates, and Projections of Urban and Rural Populations and of Urban Agglomerations*. ESA/P/WP.141, December 1997; Annex Tables 1, May 1997. New York: United Nations.

———. 1997b. *Urban and Rural Areas 1996*. Publication ST/ESA/SER.A/166. New York: United Nations.

———. 1998a. *World Population Estimates and Projections, 1998 Revision. Briefing Packet*. New York: United Nations.

———. 1998b. *World Population Projections to 2150*. ESA/P/WP.145, 30 March 1998. New York: United Nations.

———. 1999. *Comprehensive Tables*. Vol. 1 of *World Population Estimates and Projections, 1998 Revision*. New York: United Nations.

United States Bureau of the Census. 1975. *Historical Statistics of the U.S., Colonial Times to 1970*. Bicentennial edition. Washington, D.C.: U.S. Government Printing Office.

Vitousek, Peter, et al. 1997a. "Human Alteration of the Global Nitrogen Cycle: Causes and Consequences." *Issues in Ecology* (Ecological Society of America), no. 1, Spring.

Vitousek, Peter, Harold A. Mooney, Jane Lubchenco, and Jerry M. Melillo. 1997b. "Human Domination of Earth's Ecosystems." *Science* 277: 494–499.

Watson, Andrew J., and Peter S. Liss. 1998. "Marine Biological Controls on Climate via the Carbon and Sulfur Geochemical Cycles." *Philosophical Transactions of the Royal Society of London* B 353: 41–51.

Wattenberg, Ben J. 1997. "The Population Explosion Is Over." *The New York Times Magazine*, 23 November, pp. 60–63.

Williams, James H. 1997. "The Diffusion of the Modern School." Pp. 119–136 in *International Handbook of Education and Development: Preparing Schools, Students, and Nations for the Twenty-First Century*, ed. William K. Cummings and Noel F. McGinn. New York, Tokyo: Pergamon, Elsevier Science.

Woodward, F. I., M. R. Lomas, and R. A. Betts. 1998. "Vegetation-Climate Feedbacks in a Greenhouse World." *Philosophical Transactions of the Royal Society of London* B 353: 29–39.

World Bank. 1993. *World Development Report: Investing in Health*. New York: Oxford University Press.

World Bank. 1999. *World Development Report: Knowledge for Development*. New York: Oxford University Press.

World Resources Institute. 1998. *World Resources 1998–99*. New York: Oxford University Press.

Zlotnik, Hania. 1999. "World Population Prospects—the 1998 Revision." Working paper 19, Joint ECE-Eurostat Work Session on Demographic Projections. Statistical Commission and Economic Commission for Europe, Statistical Office of the European Communities (Eurostat), Conference of European Statisticians. Rome: ISTAT (Italian National Statistical Institute).

What the Future Holds

Insights from Social Science

edited by Richard N. Cooper and Richard Layard

The MIT Press
Cambridge, Massachusetts
London, England

This book was set in Bembo in 3B2 by Asco Typesetters, Hong Kong.
Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

What the future holds : insights from social science / edited by Richard N. Cooper and Richard Layard.
p. cm.
Includes bibliographical references and index.
ISBN 0-262-03294-5 (hc : alk. paper)
1. Social prediction. 2. Forecasting. I. Cooper, Richard N. II. Layard, P. R. G. (P. Richard G.)
HM901 .W53 2002
303.49—dc21 2001032976

Contents

1 **Introduction** 1
Richard N. Cooper and Richard Layard

2 **The River and the Billiard Ball: History, Innovation, and the Future** 17
Peter Schwartz

3 **The Future of Population** 29
Joel E. Cohen

4 **The Future of Energy from the Perspective of the Social Sciences** 77
Clark C. Abt

5 **Modeling Climate Change Impacts and Their Related Uncertainties** 123
Stephen H. Schneider

6 **The World of Work in the New Millennium** 157
Richard B. Freeman

7 **Threats to Future Effectiveness of Monetary Policy** 179
Benjamin M. Friedman

8 **The Architecture of Government in the Twenty-First Century** 209
Timothy Besley

9 **The Cybernetic Society: Western Future Studies of the 1960s and 1970s and Their Predictions for the Year 2000** 233
Alexander Schmidt-Gernig

Contributors 261
Index 263