Sustaining Life on the Earth

Hope for an environmentally sustainable future lies in evolving institutions, technology and global concern

by Robert W. Kates

Can life be sustained on the earth? If life is simply organic matter capable of reproducing itself, then the answer is almost assuredly "yes." Through the ages, life on the earth has survived repeated catastrophes, including atmospheric change, the submergence and reemergence of continents, and collisions with asteroids. Life will almost surely go on at least until the final "dimming of the light" of a cooling sun. But if life on the earth is life as we know it, the mix of living things that fill the places we are familiar with, then the answer is almost assuredly "no." For human-induced modifications to the environment, including to the global biogeochemical and hydrologic cycles, rival nature's changes to the earth. Most of the transformations of the past 10,000 years have occurred in our lifetimes, as humans continue to alter their environment in increasingly diverse ways.

If by life we mean us, our species and the life that supports us, then the answer is "perhaps." For humans, life has never really been simply a progression onward and upward from the cave. Our numbers have grown by fits and starts, our civilizations have declined and fallen, and even our physique has fluctuated over time. But since the middle of the last century our population has

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POPULATION MEETS NATURE in Ålesund, Norway, an island city in the Sunnmøre district that serves as a center for trading and fishing. The inhabitants of Ålesund also work in engineering firms and on some small farms (*see island in background at right*). In this northern temperate region, use of renewable resources and careful planning of manufacturing, business, agriculture and housing create a human community sustainable within the environment.

quadrupled, and projections from the United Nations and the World Bank suggest that it will at least double again by the middle of the next century. Economic activity amplified by technology has already transformed the earth.

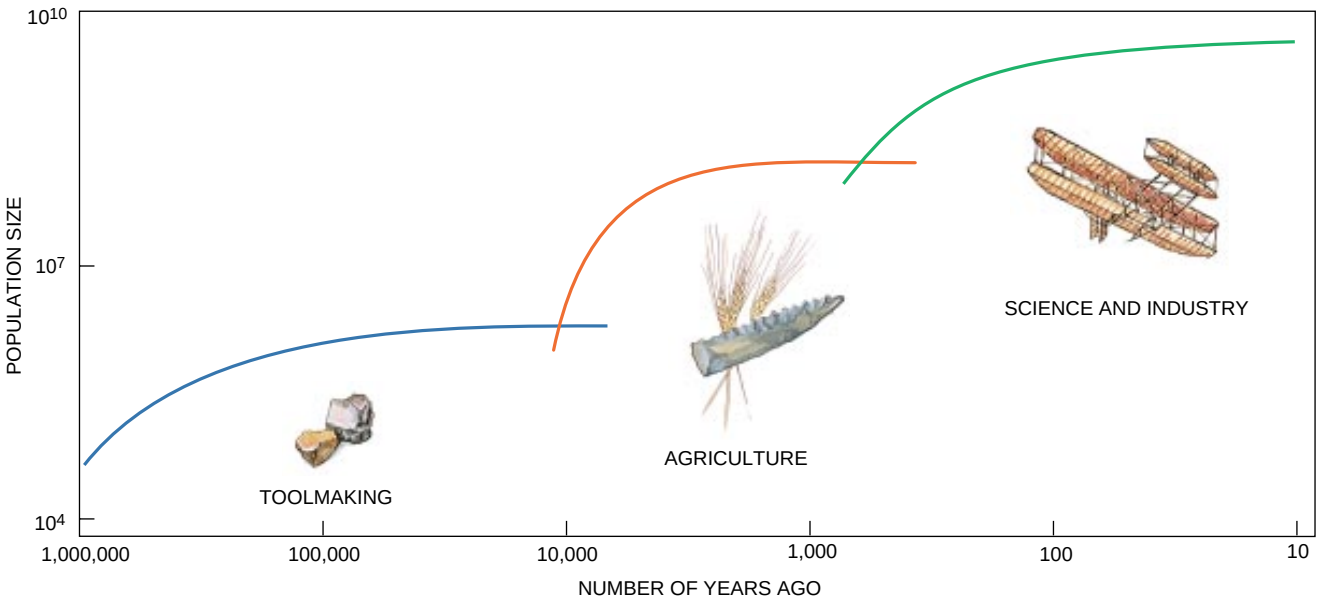
What will be the impact of such numbers of humans, their rapidly changing patterns of habitation and their growing production and consumption, on the natural systems that support life? If we can manage the transition to a warmer, more crowded, more connected but more diverse world, there may be promise of an environmentally sustainable future.

A recurring vision of the growth of world population is the exponential curve, which Thomas Robert Malthus proposed would eventually plunge when some maximum is reached. But this image, reminiscent of an accelerating rocket climbing out of sight toward sudden disaster, is misleading. Edward S. Deevey, Jr., offered a different view 34 years ago [see "The Human Population," SCIENTIFIC AMERICAN, September 1960]. He estimated the size of human population back as far as the origin of our species, plotting it on a logarithmic scale. Deevey's sensitive, extended analysis revealed three surges in the number of people.

Each surge coincided with a remarkable technological revolution: the emergence of toolmaking, the spread of agriculture and the rise of industry. Each transformed the meaning of resources and increased the carrying capacity of the earth. Each made possible a period of exponential growth followed by a period of approximate stability. The toolmaking, or cultural revolution, which began around one million years ago, saw human numbers rise to five million. Over the next 8,000 years, as humans domesticated plants and animals and invented agriculture and animal husbandry, the population grew 100-fold, to about 500 million. Now in this, the third population surge, we already number 5.6 billion—at best the midpoint on a projection that shows a doubling or even a tripling before growth levels off again—only 300 years after the scientific-industrial revolution began.

Even the global trend masks the existence of a deeper level of complexity. From its probable start in Africa, human life has steadily spread to every corner of the globe, including Antarctica, where research bases have altered the barren landscape. But although the potential for humans to survive and even flourish in the most inhospitable of places has been realized, the history of life in certain ancient areas has been one of notable fluctuation.

My colleagues Thomas R. Gottschang of the College of the Holy Cross, Douglas L. Johnson and Billie L. Turner II of Clark University and Thomas M. Whitmore of the University of North Carolina at Chapel Hill and I have studied the phenomenon. To do so, we tried to reconstruct long, continuous series of human habitation for those places where we could correlate archaeological and historical accounts. Our original goal was to extend the record of habitation in order to relate fluctuations in natural processes such as climatic variation or soil formation to more rapidly changing patterns of human activity. Combining our data, we were able to reconstruct a long-term population sequence for four ancient regions: the Nile Valley (6,000 years), the Tigris-Euphrates low-



HUMAN POPULATION has grown dramatically over the past one million years. It has done so in three stages, each followed by a plateau. The first major growth, from 150,000 to five million, coincided with the development of toolmaking. The second surge, from five million to 500 million, was associated with the advent of agriculture. The third, from 500 million to 5.6 billion, is a consequence of the rise of industrial civilization. Each technological revolution—toolmaking, agriculture and manufacturing—has enabled humans to lessen their direct dependence on natural systems.

lands of Iraq (6,000 years), the basin of Mexico (3,000 years), and the central Maya lowlands of Mexico and Guatemala (2,200 years).

These reconstructed population series all show periodic fluctuations in growth and decline; in none does population grow without interruption. In all except the Maya case (the shortest record), there are 2.5 waves evident in which population at least doubled over the previous base and then fell by at least half with respect to that high point. The rates of growth and decline are modest in the early waves and more drastic in the later ones. The collapses of civilization, though surely catastrophic to the inhabitants, are not sudden. The second wave of declines, averaged for the four regions, lasts 500 years even though it includes one of the most precipitous extinctions in human history: the 16th-century epidemics among the native peoples of the New World.

Fluctuations in the well-being of entire civilizations are mirrored in the well-being of individuals. Again, seeking the long view of human life, my colleagues at Brown University—Robert S. Chen, William C. Crossgrove, Jeanne X. Kasperson, Robley Matthews, Ellen Messer, Sara R. Millman and Lucile F. Newman—and I considered human height. We assembled estimates, made by others, usually from the skeletons of adult males. We also considered studies of the measured heights of people from institutionalized populations. It is widely accepted that height, standardized by age and averaged over a population, reflects the state of nutrition and illness. In this way, times of hunger and ill health can be distinguished from those of plenty and wellness. Our analysis shows that throughout history, height, and presumably well-being, has fluctuated. To take one example, an adult male in Roman Britain was as tall as or taller than his counterparts in this century, but his Victorian descendants were shorter. Thus, improvement in diet, health and sustenance has traced a halting, sometimes retrograde course.

These long waves of growth and decline in certain areas (which we have called millennial-long waves) raise questions about human life on the earth. Previously, the fates of particular places apparently averaged out—some developed, and others declined, with the overall balance one of punctuated growth. Has the scientific-industrial revolution, and the global economy to which it gave rise (complete with a global famine response system), exempted us from Malthusian-like collapses of the past? Or can particular regions, perhaps even regions that are world leaders, collapse in modern times?

Modern civilization has profoundly altered the environment. Concern about such effects has a history that extends back at least a century and a half [see "Origins of Western Environmentalism," by Richard Grove; SCIENTIFIC AMERICAN, July 1992]. As early as 1864, George Perkins Marsh published a benchmark assessment, *Man and Nature; or, Physical Geography as Modified by Human Action.* A subsequent account, entitled *Man's Role in Changing the Face of the Earth,* appeared in 1956. The most recent study, *The Earth as Transformed by Human Action,* was published in 1990.

An international collaborative effort, the Earth Transformed Project was seven years in the planning and execution. It brought together leading scientists from 16 countries to document global and regional change over the past 300 years. We were able to reconstruct human-induced change in 13 worldwide dimensions of chemical flow, land cover and biotic diversity: terrestrial vertebrate diversity, deforested area, soil area loss, sulfur releases, lead releases, carbon tetrachloride releases, marine mammal populations, water withdrawals, floral diversity, carbon releases, nitrogen releases, phosphorus releases and sediment flows.

The investigators took stock of the extent of human impact, emphasizing in particular the past 300 years. To place current changes in long-term perspective, we estimated human influence on the earth over the past 10,000 years, since the dawn of agriculture. In that time, humans have deforested a net area the size of the continental U.S., mostly using it for cropland. Water, in an amount greater than the contents of

Lake Huron, is diverted every year from the hydrosphere for human use. Half the ecosystems of the ice-free lands of the earth have been modified, managed or utilized by people. The flows of materials and energy that are removed from their natural settings or synthesized now rival the flows of such materials within nature itself.

Most of this change has been extremely recent, considering that in seven of the 13 dimensions, half of all the change during the past 10,000 years happened within our lifetimes. To these rapid global environmental changes, it has now become fashionable to link threats emanating from political upheaval. Wars, especially in developing countries, are frequently attributed to famine, environmental disasters or scarcity of natural resources.

Here, where I live and write, on the coast of Maine, far from these disasters, I ask myself what might occur in the coming century. I have very good reasons to do so: six grandchildren who will be in their sixties and seventies by the year 2050. As I struggle to imagine their world, the ever present ocean suggests a metaphor of change that comes as currents, tides and surges. The currents are the long-term trends, the tides are the cyclical swings, and the surges, undertows and riptides are the surprises.

In particular, I believe the world of the next century will be warmer and more crowded, more connected but more diverse. Environmental change, population growth and increasing connectedness and diversity are powerful trends as deep-running as the ocean currents, seemingly set in place with little possibility of reversal, though clearly subject to slower or more rapid movement. Unless there is some flaw in present-day scientific understanding, we are already deeply committed to a warmer earth. Our world has been made more connected by a global economy and the widespread availability of rapid communication and transportation technology. This increasing connectedness will not necessarily homogenize people beyond their common affection for Coca-Cola, but it may, paradoxically, increase the diversity of both individuals and things. Goods, information and people are generally drawn to places of wealth or opportunity, which can make such areas more diverse. And strong countercurrents that emphasize ethnic, national and religious distinctiveness may create eddies and whirlpools where differing currents can mix and clash.

At the opposite extreme from the currents of certainty are the undertows, riptides and storm surges that batter our conventional expectations, leaving us only with the wisdom to expect surprises. National boundaries that had seemed immutable for decades have been swept away in a matter of months. Reaction to specific crises can deepen into new norms of human behavior and interaction. The spread of diseases such as AIDS can eat away at the foundations of society, increasing the potential for unforeseen disaster.

In contrast to the long-term trends and surprises, there are the short-term cycles or tides that are superimposed on the great underlying currents. As illustrations of the very short term, consider the oscillations of the business cycle or the so-called El Niño phenomenon that affects the Pacific Ocean and environs at irregular intervals of years. There are also decades-long fluctuations: in democracies, for instance, swings to the left or right of the political spectrum recur, as do periods of economic expansion and contraction.

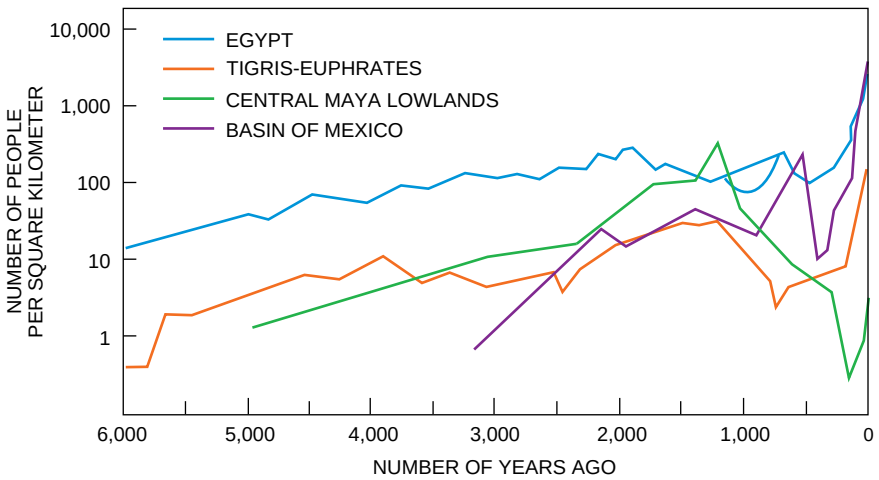
Among these tides and storms, humans question their chances for long-term survival. Can our population continue to double and redouble within our children's and their children's lifetimes? Will there be food enough to feed the many, material sufficient for their needs and desires, and energy available to move and transform materials? Will the side effects of creating and using energy and of making and shaping materials undermine human health and destroy the ecological systems on which our species ultimately depends?

Such questions were powerfully posed 200 years ago by Malthus in his *Essay on the Principle of Population* (1798). They may be older yet: Tertullian wondered 1,800 years ago whether "pestilence, and famine, and wars, and earthquakes have to be regarded as a remedy for nations, as a means for pruning the luxuriance of the human race." It is not unexpected that Malthus, who was born in 1766 and died in 1834, worried about the adequacy of the resource base to feed England, because he lived in the midst of a population explosion. We now know that in the decade of his birth, England and Wales grew by 7 percent; in the decade of the first edition of his essay, by 11 percent. By the time of the fifth edition, in 1817, decadal growth had peaked at 18 percent.

Nor is it surprising that these concerns reemerge in the post–World War II world. The population explosion of the developing world was recognized in the late 1940s and the early 1950s. Indeed, the tides of scientific and public concern over population, food, materials, energy and pollution have surged, ebbed and surged again during the past 45 years, emerging most recently on the eve of the new millennium.

Among the threats that are most likely to occur, cause the most harm or affect the most people, I can identify three areas of concern. The first is the introduction of pollutants: acid rain in the atmosphere, heavy metals in the soils and chemicals in the groundwater. Humans also face the global atmospheric dangers of nuclear fallout, stratospheric ozone depletion and climatic warming from greenhouse gases. Finally, a massive assault on the biota has resulted from deforestation in the tropical and mountain lands, desertification in the drylands, and species extinction, particularly in the tropics.

A surge in production and consump-



ADVANCE AND RETREAT of population density during historical times in four regions indicate that human numbers can fluctuate significantly. Civilizations in the Maya lowlands, the Tigris-Euphrates basin, the basin of Mexico and Egypt show periods of growth and decline. Is modern industrial society immune to this pattern?

tion of material goods accompanies the rise in our numbers. In 1989 the International Institute of Applied Systems Analysis examined "current trends" or "business as usual" projections for a doubling of population. Its analysis assumed that varied and nutritious diets, industrial products and regular jobs are to be within reach of most of the 10 billion people. Thus, a doubling of the population will probably require a fourfold increase in agricultural production, a sixfold rise in energy use and an eightfold increase in the value of the global economy.

Many experts find this 2–4–6–8 scenario unbelievable and certainly unsustainable. Such increases, they think, could not be accommodated by present technology and practice in an environment that has already seen substantial transformation of its atmosphere, soils, groundwater and biota. Indeed, for many of today's Jeremiahs—Lester R. Brown, Paul R. and Anne H. Ehrlich, Donella H. Meadows, Dennis L. Meadows and Jørgen Randers—a world of more than five billion people is already overpopulated because virtually every nation is depleting its resources or degrading its environment. Other economists and technologists disagree [see "Can the Growing Human Population Feed Itself?" by John Bongaarts; SCIENTIFIC AMERICAN, March]. They believe the invisible hand of rising prices will curb consumption and encourage conservation and invention. They are confident that human creativity can overcome all limits.

But most of us, on reflection, recognize the unique situation that we face. In an extraordinarily short period—a matter of decades—society will need to feed, house, nurture, educate and employ at least as many more people as already live on the earth. If in such a warmer, more crowded world environmental catastrophe is to be avoided, it can be done only by maintaining severe inequities in human welfare or by adopting very different trajectories for technology and development.

How likely are we to have such different trajectories for technology and development? I draw cautious encouragement from two sets of trends that I perceive but do not fully understand. The first set relates to changes already apparent in the currents carrying us into the future. The second set relates to human adaptability in the form of the emergence of new institutions, technologies and, probably most important, ideas.

To illustrate some favorable changes in the currents, consider the *IPAT* equation. Initially formulated by Paul Ehrlich of Stanford University and John P. Holdren of the University of California at Berkeley, it is now widely used as a simplified statement of the driving forces of the human-induced detrimental impacts on the environment. The impacts term (I) is a function of population (P), the level of affluence (A) and the technology (T) available. Thus, the formulation captures the widespread agreement that to the extent that the environment is endangered, it is so not just because of the enormous growth of population (a common view in industrial countries) or just because of the rapacious and still growing use of energy and materials by affluent countries (a common view in poor countries). Instead both are significant contributing reasons. Estimates of the sources of greenhouse gases, for example, presume that most of these compounds originate in rich countries, but developing nations will contribute almost as much or more in 20 to 30 years if present trends persist. The technology term also captures the potential of science, technology and society to alter the impacts of any given level of population and affluence.

The growth of population and affluence and the spread of technologies are large-scale currents propelling us toward the warmer, more crowded, more connected but more diverse world. Countercurrents are already at work for each of the *IPAT* variables. Growth is slowing, and limits are in sight. Consider population and return to Deevey's vision of populations in flux. We are now in the last phase of the third major population surge, the completion of a demographic transition from a world with high rates of births and deaths to one with low rates. It took 150 years to complete this transition in England, but the transition in developing nations is occurring much more rapidly than expected.

Birth rates have fallen considerably from their post–World War II peak of five births per woman. The shift to 2.1 births per woman, required for zero-population growth, is just over halfway complete: the current birth rate is 3.2. The transition to low death rates is more advanced. In developing countries after World War II, the life expectancy at birth was 40 years. Now it has increased to 65 years, two thirds of the way to a likely average of 75 years, if we use developed countries as a model. The slowing of the rate of population growth everywhere, even very modestly in Africa, is a source of encouragement for sustaining life on the earth.

The affluence term may also be self-limiting: "Richer is cleaner." The Earth Transformed Project notes that the rates of increase for five of the 13 transformations studied have now turned downward: they are vertebrate and marine mammalian extinctions, as well as the release of lead, sulfur and carbon tetrachloride. All these have been the object of strenuous regulatory attention from the wealthier countries. A 1992 World Bank report argues that environmental problems shift with affluence. The poorest countries concentrate on primary needs for housing and sanitation, whereas in middle-income developing coun-

Height and Technological Change

Average height, a standard measure of general well-being, has fluctuated over time. Hunter-gatherers in the eastern Mediterranean, who benefited from a diet full of calories and protein, reached a height of five feet, 10 inches. Early agriculturists from that area reached only five feet, three inches. They lived on a heavy cereal diet and suffered physical wear and tear from the difficult work of farming. Late agriculturists in Europe averaged five feet, nine inches. They presumably benefited from improvements in agricultural and other technologies. Stature fell again at the beginning of the European industrial period, when men reached five feet, seven inches on average. Modern U.S. men are slightly taller.

PREAGRICULTURAL EASTERN MEDITERRANEAN (30,000–9,000 years ago)

tries, efforts have shifted to grappling with air and water pollution. In the richest of countries, the focus has shifted from addressing localized problems to dealing with global environmental problems.

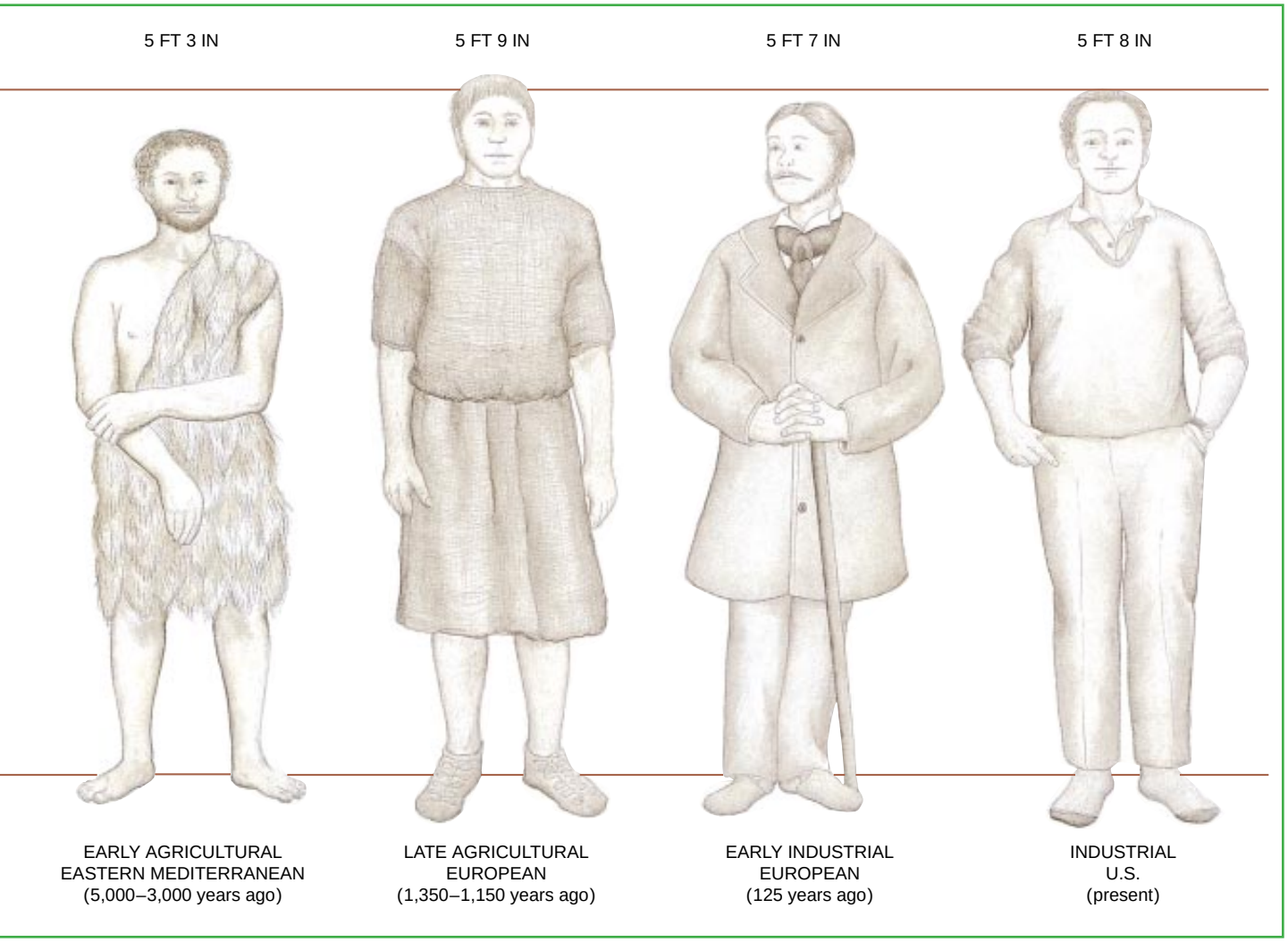
Economic and technological forces encourage reductions in the use of materials and energy in manufacturing: "Doing more with less." Since the mid-19th century the amount of carbon used per unit of production has been decreasing yearly by 1.3 percent through a combination of using less carbon-rich fuels (0.3 percent) to produce energy and using less energy overall per unit of production (1 percent). Nevertheless, these improvements in energy use have not been sufficient to offset the annual growth of the economy (3 percent). This has led to a global rise in carbon dioxide emissions of 1.7 percent every year.

A similar but more complicated trend toward dematerialization involves fewer materials per unit of production. We are using less steel and cement but more aluminum and chemicals (although use of the last two has peaked and is beginning to decrease). Despite the computer and television revolutions, the use of paper remains constant.

We should reconsider impacts as well. Scientists often do not sufficiently understand the effects of human-induced changes on the natural systems that support us to know how much or whether they are threatened or what replaces them when they are degraded. An apparent bias in research encourages the identification of harmful effects rather than the determination of negative feedback cycles that moderate the damage. For example, recent documentation shows that forest biomass in Europe is not only surviving but probably increasing, despite enormous burdens of pollutants and acid rain. That such a revitalization can happen, possibly through fertilization by the very same chemical pollutants that are causing the damage, is a caution. Nature may be more robust than popular rhetoric is willing to concede.

Optimists cite these countercurrents as good news. They argue that the trends, though insufficient to overcome the global growth in population or economy, are at least heading in the right direction. Pessimists either ignore the countercurrents or see them simply as too little and too late. It would help both sides to understand the many forces that are at work, invisible or otherwise. As yet, perception is quite dim. Consider the trend in population: What forces have lead to a decline in fertility?

A large amount of research has sought to estimate the dynamics and relative contributions of economic and social development and organized family-planning programs to the decline in births. Several studies, covering most developing countries, have found that increases in development are strongly associated with decline in birth rate, accounting for about two thirds of the drop. Additional research indicates that organized family-planning programs contribute another 15 to 20 percent to fertility reduction. Although only a few



reports included culture and ethnicity, these factors also appear to be important. Socioeconomic development and substantial family-planning programs seem to be most effective in East and Southeast Asia or among those of Chinese extraction. Such programs are also effective when carried out on small, crowded islands or in city-states.

If, as the studies seem to show, "development is the best contraceptive," it is not clear which aspects of development are most influential. Analysts argue that as development proceeds, it lessens the need or desire for more children because more children survive, decreases the need for child labor and increases the need for educated children. Development also cuts the time available for childbearing and rearing and creates more opportunity for women to gain an education and find salaried work. Finally, it improves access to birth-control technology. Advocates for a particular policy usually single out one of these themes to justify their programs, but it is clear that better child survival, changing needs for labor, improved opportunities for women and access to birth control all occur together during the course of development.

Our understanding of the decline in fertility, as well as of the dynamics of pollution control and decarbonization of fossil fuels, remains opaque. For all these issues, there is no shortage of favored, oversimplified explanations to describe the countercurrents. And as with the fertility decline, a tension exists between separating the effects of such catchalls as "development" and "affluence" from the organized efforts of science or society.

The changes necessary to mitigate the extraordinary demands being placed on our life-support systems require a more fundamental understanding of our impacts on the earth. But the world does not and should not wait for such understanding. We know we must accelerate favorable trends and halt destructive ones. A species capable of questioning its own survival can also struggle to adapt to the warmer, more crowded and more connected world. New institutions, new technologies and new ideas are already in place, defining a different trajectory of technology and development that a sustainable future might follow.

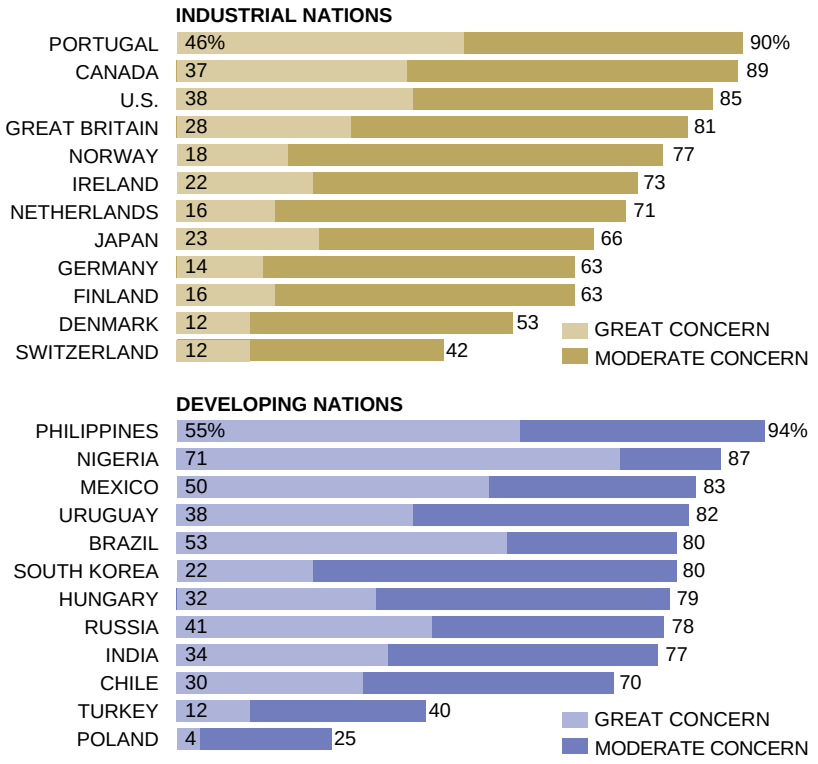
In a more connected but more diverse world, three sets of important transnational institutions are emerging. The best known are those created by governments, a set of international organizations, treaties and activities. Currently some 170 international treaties-in-force focus on the environment. New international institutions such as the United Nations Commission on Sustainable Development will oversee the accords of the 1992 Earth Summit in Rio de Janeiro. The Global Environmental Facility combines the talents and wealth of the World Bank and the U.N. Development (UNDP) and Environment (UNEP) Programs. Equally well known, but not usually for its environmental dimension, is the transnational corporation. Such corporations are responsible for many of the human-induced changes taking place around the globe; increasingly, however, they are also disseminators of common approaches, technical skills and standards for addressing environmental problems. Finally, least considered, but in many ways most important, is the veritable explosion of transnational nongovernmental and private voluntary environment and development organizations and their local counterparts in developing countries—an estimated 200,000 groups, increasingly linked together in international networks.

In a more crowded and more consuming world, one mode of coping is to use technology that requires modest amounts of such basic ingredients as energy, materials and information. As shown by long-term trends, there has already been a reduction of energy and materials required per unit of economic output, and the potential exists to accelerate such trends. Simple interventions include the recent competition to build a low-energy-consuming, non-ozone-depleting refrigerator, which will soon be on the market in the U.S. Another, related effort is the one to move immediately to next-generation refrigeration in India. In some eastern European countries, telephone companies are moving directly to wireless communications systems instead of rebuilding the fraying wire infrastructure.

The emergent field of study and action known as industrial ecology seeks to use the mechanisms of market com-

Environmental Concern Is Global

Despite the differences in population growth rates, available technology and level of affluence, people in industrial and developing nations share concern about the impact of human activities on the earth. A 1993 Gallup poll asked respondents in 24 countries, "How concerned are you personally about environmental problems?" Answers indicating "great concern" or a "fair amount of concern" generally dominated.



SOURCE: Health of the Planet, *George H. Gallup, International Institute, 1993*

GLOBAL VILLAGE includes American Samoa, where inhabitants watch television by the edge of the Pacific. Humankind needs to make a transition to a more crowded, warmer, more connected world while avoiding widespread catastrophe.

petition and efficiency to minimize the amount of energy, materials and waste. Further into the future lies the substantial opportunity to increase human sustenance without increasing environmental burdens. The goal may be achieved through the science and engineering of biological processes, the development of new energy sources and transmission technologies, the creation of materials and, ultimately, the substitution of information for both energy and materials. Biotechnology promises crops that require less fertilizer and fewer pesticides. Researchers in the miniature world of nanotechnology and microelectronics hope to develop machines and processes that will require less bulk and thus less waste.

Potentially more significant than new institutions or technology are new ideas combined with an ever increasing concern for the environment. Sustaining human life on the earth requires at least three crucial sets of ideas: that cohabitation with the natural world is necessary; that there are limits to human activity; and that the benefits of human activity need to be more widely shared.

These ideas are spreading: last winter I heard a concert of 500 schoolchildren's voices, my grandchildren's included. Most striking to me was the relative absence of the patriotic songs of my childhood and their replacement by environmental hymns and anthems. I came away marveling at how 25 years of Earth Days have changed the formative ethos of young Americans. But this is Maine—what of the rest of the world?

A 1993 study undertaken by Riley E. Dunlap and the Gallup organization compared opinion on environmental issues in 12 industrial and 12 developing nations (including eastern Europe) and found surprisingly little difference in their attitudes. Even the attribution of the cause of the problems—"overpopulation" and "consumption of the world's resources by industrial countries"—is seen as contributing equally by residents of both rich and poor countries. Along with this widespread evidence of environmental concern, more profound ideas are emerging. Witness the ongoing fundamental challenges to anthropocentrism and the more modest efforts to resolve the conflicting needs of ecosystems and economies or the conflicting claims of equity between species, places, peoples, livelihoods and generations.

Fifteen years ago Lionel Tiger of Rutgers University suggested that there was a "biology of hope," an evolutionary human tilt toward optimism that compensates in part for our ability to ask difficult questions such as "Can human life on the earth be sustained?" Although unpersuaded by his somewhat tenuous chains of argument, I share his inclination. Not because I have excessive confidence in the invisible hand of the marketplace, or of technological change, or even of James E. Lovelock's Gaia principle, in which life itself seems to create the conditions for its own survival. Nor is it just the wisdom and energy of my grandchildren and their enormous cohort of wise and energetic children around the world. Rather it is because hope is simply a necessity if we as a species, now conscious of the improbable and extraordinary journey taken by life in the universe, are to survive.

FURTHER READING

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