Thirty-five years ago, Science published a remarkable essay by Garret Hardin entitled “Tragedy of the Commons.” I knew Hardin at the time and admired his paper, but had no idea whatsoever of the influence it and its author would have on how we think about population and the environment. That influence has spawned several successor strands. One, evident almost immediately, was an enhanced concern about the impact of population growth on resource utilization. The second was a delayed argument about how to consider population growth in policy terms—an argument to which Hardin later added combustible material with a piece called “Lifeboat Ethics” that struck many as elitist or hard-hearted. The third, much later, is a recent social science literature revising Hardin’s hard choice (either a coercive consensus to limit breeding or repressive government controls) by showing that groups often evolve fair social arrangements that limit exploitation and conserve shared resources.

The population/resource collision has only grown more important since Hardin’s Science essay. Earth’s population then was about 3.5 billion; it has since grown by a factor of nearly 2, to 6.3 billion. That growth, amplified by global increases in affluence and the power of technology, has brought escalating pressures on “common-pool” resources such as air, fresh water, and ocean fisheries that are accessible to many potential harvesters who can extract marginal personal benefits at a cost that is low because all other harvesters share it. Decades of depletion of these resources, whose status was explored in the past four issues of Science, have led to new concerns and new terms: “sustainability” and “sustainability science.” The loss of value compels us to undertake more careful analyses; first, of what values we actually take from nature’s resources, and second, of how science can contribute to maintaining such resources sustainably.

We obtain value from our environment in various ways: We may use it for timber or for hunting, we may enjoy it for various nonuse values such as birdwatching, and we may extract pleasure from merely knowing that it’s there. In Man and Nature, perhaps the first environmental classic, George Perkins Marsh provided a meticulous 19th-century account of what had happened to the world’s woods, waters, and fields. In Marsh one finds a kind of outrage over environmental damage, but there is little of the sense of wonder about nature that one finds in modern writers such as Wallace Stegner. Marsh is all about use values, Stegner about nonuse. A modern convergence defines sustainability as requiring that the average welfare of the successor generation, with respect to the total of all these values, be as high or higher than that of the current generation.

That begs some important questions. What about equity? Most, I think, would insist that the condition of the majority of people, if not of everybody, should either stay the same or improve. And what about history? If welfare has been improving for several generations, is there a built-in expectation that historical rates of improvement will continue? Our welfare detectors, after all, are exquisitely sensitive to disparity.

Once we find agreement about what sustainability really means, we can ask what science might contribute. It is surely encouraging that science is focusing increasing attention on resource problems, but the success rate is not high. At small scales, where science is applied in limited societies where property rights can be made clear, there have been some real winners, such as managed preserves that blend conservation objectives with recreational values. But at large scales, ranging from ocean fisheries to global climate, good science often fails the implementation test because the transaction costs are too high or because political and economic factors intervene. A recommended target stock size for managing a marine fishery fails, although its stability makes it desirable, because to harvesters it looks too large to leave alone. Models and climate history tell us that global warming is likely to reach damaging levels, but the cost of controlling carbon emissions is high and there is always the mirage of a hydrogen economy.

The big question in the end is not whether science can help. Plainly it could. Rather, it is whether scientific evidence can successfully overcome social, economic, and political resistance. That was Hardin’s big question 35 years ago, and it is now ours.

Donald Kennedy
Editor-in-Chief
Once in a while, in our headlong rush toward greater prosperity, it is wise to ask ourselves whether or not we can get there from here. As global population increases, and the demands we make on our natural resources grow even faster, it becomes ever more clear that the well-being we seek is imperiled by what we do. Therefore, in an effort to encourage constructive thought about our collective future, we commissioned a group of short Viewpoints about some of the common resources—air, fresh water, fisheries, food and soil, energy—and key trends—in human population, biodiversity, and climate—that are most important for our general well-being. These articles, assembled as a 4-week-long series beginning in this issue called the “State of the Planet,” are brief overviews of the current states of affairs of those areas, and how things might change in the near future. They are meant not as answers but as stepping-off points. However, what is done with information is as important as the information itself. Therefore, on 12 December, immediately following this series, we will present a special issue on the “Tragedy of the Commons,” the classic metaphor of the late Garret Hardin which appeared 35 years ago, in which some contemporary ideas about the management of shared resources will be discussed.

Nothing affects our impact on the planet more than our number. Therefore, we begin the State of the Planet series with “Human Population: The Next Half Century,” by Joel E. Cohen, which examines the recent history of human population and predicts how it might change over the next 50 years. Next, Martin Jenkins discusses trends in biodiversity, the causes of these trends, and what they mean for human survival, in “Prospects for Biodiversity.”

In the following weeks, we will focus more on specific resources. On 21 November, Michael Stocking examines the quality and health of tropical soils and food supplies in “Tropical Soils and Food Security.” Accompanying that, Daniel Pauly et al. consider our marine food reserves in “The Future for Fisheries.” On 28 November, the series continues with an examination of water availability, “Global Freshwater Resources: Soft-Path Solutions for the 21st Century” by Peter Gleick. Then, Raymond J. Chow et al. discuss the resource most vital to the economic and technological growth that are so universally sought, in “Energy Resources and Global Development.” In the final issue of the series, on 5 December, Hajime Akimoto presents an overview of “Global Air Quality and Pollution,” something that until fairly recently was considered a local or regional issue. We conclude with “Modern Global Climate Change” by Thomas R. Karl and Kevin E. Trenberth, in which they discuss what is undoubtedly one of the most pressing issues of our time. Links to all of the articles in the series, as well as to Web resources accompanying each article, can be found at www.sciencemag.org/sciext/sotp.

This collection of articles is offered in the spirit of “forewarned is forearmed,” not “the sky is falling.” Whether we find ourselves forewarned or under the fallen sky depends largely on what we choose to do about these issues over the next generation.

—H. JESSE SMITH
By 2050, the human population will probably be larger by 2 to 4 billion people, more slowly growing (declining in the more developed regions), more urban, especially in less developed regions, and older than in the 20th century. Two major demographic uncertainties in the next 50 years concern international migration and the structure of families. Economies, nonhuman environments, and cultures (including values, religions, and politics) strongly influence demographic changes. Hence, human choices, individual and collective, will have demographic effects, intentional or otherwise.

It is a convenient but potentially dangerous fiction to treat population projections as exogenous inputs to economic, environmental, cultural, and political scenarios, as if population processes were autonomous. Belief in this fiction is encouraged by conventional population projections, which ignore food, water, housing, education, health, physical infrastructure, religion, values, institutions, laws, family structure, domestic and international order, and the physical and biological environment. Other biological species are recognized explicitly only in the recent innovation of quantifying the devastating demographic impacts of HIV and AIDS. The absence from population projection algorithms of influential external variables indicates scientific ignorance of how external variables influence demographic rates rather than any lack of influence (1).

Demographic projections stimulate fears of overpopulation in some, fears of demographic decline and cultural extinction in others (2). This review of current projections for the next half century will not attempt to assess the implications of likely demographic changes for health, nutrition, prosperity, international security, the physical, chemical and biological environment, or human values. Other articles in this series cover such topics.

Past Population
Earth's population grew about 10-fold from 600 million people in 1700 to 6.3 billion in 2003 (3). These and all demographic statistics are estimates; repeated qualifications of uncertainty will be omitted. It took from the beginning of time until about 1927 to put the first 2 billion people on the planet; less than 50 years to add the next 2 billion people (by 1974); and just 25 years to add the next 2 billion (by 1999). The population doubled in the most recent 40 years. Never before the second half of the 20th century had any person lived through a tripling. The human species lacks any prior experience with such rapid growth and large numbers of its own species.

From 1750 to 1950, Europe and the New World experienced the most rapid population growth of any region, while the populations of most of Asia and Africa grew very slowly. Since 1950, rapid population growth shifted from Western countries to Africa, the Middle East, and Asia.

The most important demographic event in history occurred around 1965–70. The global population growth rate reached its all-time peak of about 2.1% per year (pa). It then gradually fell to 1.2% pa by 2002 (4). The global total fertility rate fell from 5 children per woman per lifetime in 1950–55 to 2.7 children in 2000–05. The absolute annual increase in population peaked around 1990 at 86 million and has fallen to 77 million. Concurrent trends included worldwide efforts to make contraception and reproductive health services available, improvements in the survival of infants and children, widespread economic development and integration, movements of women into the paid labor market, increases in primary and secondary education for boys and girls, and other cultural changes.

In 1960, five countries had total fertility rates at or below the level required to replace the population in the long run. By 2000, there were 64 countries such countries, with about 44% of all people (4, 5).

Worldwide urbanization has taken place for at least two centuries and accelerated greatly in the 20th century. In 1800, roughly 2% of people lived in cities; in 1900, 12%; in 2000, more than 47%, and nearly 10% of those city dwellers lived in cities of 10 million people or larger. Between 1800 and 1900, the number of city dwellers rose more than 11-fold, from 18 million to 200 million; between 1900 and 2000, the number of city dwellers rose another 14-fold or more, from 200 million to 2.9 billion. In 1900, no cities had 10 million people or more. By 1950, one city did: New York. In 2000, 19 cities had 10 million people or more. Of these 19 cities, only four (Tokyo, Osaka, New York, and Los Angeles) were in industrialized countries (6).

Demographic Projections of the Next 50 Years
Projections of future global population prepared by the United Nations Population Division, the World Bank, the United States Census Bureau, and some research institutions assume business as usual (7–9). They include recurrent catastrophes to the extent that such catastrophes are reflected in past trends of vital rates, but exclude catastrophes of which there is no prior experience, such as thermonuclear holocaust or abrupt, severe climate change. The following summary relies mainly on the United Nations Population Division’s urbanization forecasts (6) and World Population Prospects: The 2002 Revision (4).
Alternative projections prepared by the UN include low, medium, high and constant-fertility variants. Estimates of present levels of demographic variables are projections based on measurements in recent years, rather than global current measurements.

According to the medium variant, the world’s population is expected to grow from 6.3 billion today to 8.9 billion in 2050. Whereas the first absolute increase by 1 billion people took from the beginning of time until about 1800, the increase by one billion people from 6.3 billion to 7.3 billion is projected to require 13 to 14 years. The anticipated increase by 2050 of 2.6 billion over today’s population exceeds the total population of the world in 1950, which was 2.5 billion.

Current absolute and relative global population growth rates are far higher than any experienced before World War II. The annual addition of 77 million people poses formidable challenges of food, housing, education, health, employment, political organization and public order. Virtually all of the increase is and will be in the economically less-developed regions. More than half of the annual increase currently occurs in six countries: India, China, Pakistan, Bangladesh, Nigeria, and the United States. Of the total annual increase, the United States accounts for 4%.

Were fertility to remain at present levels, the population would grow to 12.8 billion by 2050, more than double its present size. The medium projection of 8.9 billion people in 2050 assumes that efforts to make means of family planning available to women and couples will continue and will succeed, and that after 2010 high-risk behaviors related to AIDS will become less frequent and chances of infection among those engaging in high risk behaviors will decline.

Human Population: The Next Half Century
Joel E. Cohen

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The UN’s 2002 estimate of 8.9 billion people in 2050 is 0.4 billion lower than that in their 2000 medium variant. About half of the decrease in the projection for 2050 is due to fewer projected births and an even greater decrease in projected deaths, notably from AIDS.

Global statistics conceal vastly different stories in different parts of the world. In 2000, about 1.2 billion people lived in the economically rich, more developed regions: Europe, Northern America, Australia, New Zealand, and Japan. The remaining 4.9 billion lived in the economically poor, less developed regions.

The current annual growth rate of global population is 1.22%. Rich regions’ population currently increases 0.25% annually. Poor regions’ population grows 1.46% annually, nearly six times faster. The population of the least developed regions, the 49 countries where the world’s poorest 670 million people lived in 2000, annually increases 2.41%. By 2050, the projected annual growth rate of global population is 0.33%. The poor countries’ population will still be increasing 0.4% annually, whereas the population of the rich countries will have been declining for 20 years and will then be falling at —0.14% annually. Thirty of the more developed countries are expected to have lower populations in 2050 than today, including Japan (14% smaller), Italy (22% smaller), and the Russian Federation (29% smaller). By contrast, the population of today’s poor countries is projected to rise to 7.7 billion in 2050 from 4.9 billion in 2000. Fertility in the less developed regions is expected to fall to replacement level in 2030—2035 but to remain above 2 children per woman by 2050 because some of the least developed countries will still have total fertility rates well above replacement level. The population of these high-fertility poor countries will be an increasing proportion of the population of the less developed regions.

The world’s average population density of 45 people/km² in 2000 is projected to rise to 66 people/km² by 2050. Globally, perhaps 10% of land is arable, so population densities per unit of arable land are roughly 10 times higher. In the rich countries, the population density was 23 people/km² in 2000—half the global average—and was projected not to change at all by 2050. In the poor countries, the population density was 59 people/km² in 2000 and was projected to rise to 93 people/km² in 2050. For comparison, the population density of Liechtenstein was 204 people/km² in 2000 and that of the United States was 30. A population density of 93 people/km² over the entire developing world will pose unprecedented problems of land use and preservation.

According to these projections, the ratio of population density in the poor countries to that in the rich countries is projected to rise from 2.6 in 2000 to 4.0 in 2050. Over the same interval, while the population density of Europe is projected to drop from 32 to 27 people/km², that of Africa is projected to rise from 26 to 60 people/km². The ratio of population density in Africa to that in Europe is projected to rise from 0.8 in 2000 to 2.2 in 2050. It seems plausible to anticipate increasing human effects on the natural environment in Africa and increasing pressure of migrants from Africa to Europe.

The difference in population growth rate between rich and poor countries affects both population size and age structure. If a population grows slowly, the number of births each year nearly balances the number of deaths. As most deaths occur at older ages, the numbers of individuals in different age groups are roughly equal up to older ages. The so-called population pyramid of a slowly growing population resembles a column (Fig. 1, middle row left) (10). If a population grows rapidly, each birth cohort is larger than its predecessor and the population pyramid is triangular (Fig. 1, middle row right). The projected difference in age structures between the European Union versus North Africa and western Asia (Fig. 1, bottom) has obvious implications for the supplies of military personnel and ratios of elderly to middle-aged.

Inequality in the face of death between rich and poor will decrease but remain large if survival improves everywhere as anticipated in the coming half century. Global life expectancy in 2000–05 is estimated at 65 years; in 2045–50, at 74 years. Over the same interval, life expectancy in the rich countries is expected to rise from 76 years to 82 years and in the poor countries from 63 years to 73 years. The average infant born in a poor country had a chance of dying before age 1 that was 8.1 times higher than that in a rich country in 2000–05; the same ratio is projected to be 5.2 in 2045–50.

Despite higher death rates, poor countries’ populations grow faster than those of rich because birth rates in poor countries are much higher. At current birth rates, during her lifetime, the average woman in the poor countries bears nearly twice as many children (2.9) as in the rich countries (1.6). By 2050, according to the medium variant, the total fertility rate in today’s poor countries will drop to 2.0. The total fertility rate in today’s more developed countries is projected to rise to almost 1.9 children per woman, as timing effects that currently depress the total fertility rate cease to operate.

In the coming decade, more than half of all people will live in cities, for the first time in human history. Almost all population growth in the next half century will be in cities in poor countries while the world’s rural population will remain flat, near 3 billion people.

The United Nations Population Division projects urban population only as far as 2030 (6). Its figures on urbanization disguise major ambiguities and variations among countries in definitions of “cities” and “urban.” Nevertheless, the trend toward urbanization is clear. Of the projected 2.2-billion increase in population from 2000 to 2030, 2.1 billion will be in urban areas, and all but 0.1 billion of that urban increase will be in developing countries. The annual rate of increase of urban population over the next 30 years, 1.8%, is nearly twice the projected annual rate of increase of global population during that period. The urban population of developing regions will grow rapidly as people migrate from rural to existing urban areas and transform rural settlements into cities. The rural population of the rich countries peaked around 1950 and has slowly declined since then. The rural population of the presently poor countries is expected to peak around 2025 and then gradually decline. Urbanization of the rich countries will continue, rising from 75% of people in 2000 to 83% in 2030. Over the same period, urbanization of the poor countries will rise from 40% to 56%, similar to the level of urbanization in the rich countries in 1950.

The coming half century will see dramatic population aging, which means a higher proportion of the population in elderly age groups. The proportion of children aged 4 years and under peaked in 1955 at 14.5% and gradually declined to 10.2% in 2000. By contrast, the fraction of people aged 60 years and older gradually increased from a low of 8.1% in 1960 to 10.0% in 2000. Each group constitutes about 10% of humanity today. The 20th century will probably be the last in which younger people outnumbered older ones. Children aged 0 to 4 are projected to decline to 6.6% of global population by 2050, whereas people aged 60 years and older are projected to more than double to 21.4%. By 2050, there will be 3.2 people aged 60 years or older for every child 4 years old or younger. This reversal in the numerical dominance of old and young reflects improved survival and reduced fertility. Improved survival raised the global average length of life from perhaps 30 years at the beginning of the 20th century to 65 years at the beginning of the 21st. Reduced fertility rates added smaller cohorts to the younger age groups.

Because the populations of the poor countries have been growing more rapidly than those of the rich, they have a much higher fraction of people under the age of 15 years (33% versus 18% in 2000). By 2050, in the medium variant, these fractions will drop to 21% and 16% in poor and rich countries, respectively. The global
fraction of the elderly population (aged 65 years or more) will rise from 7% in 2000 to 16% by 2050. Over the same period, the elderly fraction will rise from 5 to 14% in the presently poor countries and from 14 to 26% in the rich countries. Though the fraction of children in the population will decrease by more in the poor countries than in the rich, the fraction of elderly will increase by more in the rich countries than in the poor. Both shifts will have consequences for spending on the young and the old.

Slowly growing populations have a higher elderly dependency ratio (the ratio of the number of people aged 65 and older to the number aged 15 to 64), while rapidly growing populations have a higher youth dependency ratio (the ratio of the number of people aged 0 to 14 to the number aged 15 to 64). The elderly dependency ratio rose from 1950 to 2000 at a rapid rate in the more developed countries, slightly less rapidly in the United States, and still less rapidly in the world as a whole. The ratio rose only slightly in the less developed countries, and hardly at all in the least developed countries. After 2010, in the more developed countries, the United States, and the less developed countries, the elderly dependency ratio will increase sharply faster; this acceleration will be greater in the more developed countries and the United States. The least developed countries will experience a slow increase in the elderly dependency ratio after 2020 and, by 2050, will be approaching the elderly dependency ratio of the more developed countries in 1950.

Demographic Uncertainties: Migration and the Family

According to the United Nations Population Division, “International migration is the component of population dynamics most difficult to project reliably. This occurs in part because the data available on past trends are sparse and partial, and in part because the movement of people across international boundaries, which is a response to rapidly changing economic, geopolitical or security factors, is subject to a great deal of volatility” (11). The UN’s 2002 medium variant posits migration from less to more developed regions of 2.6 million people annually during 1995–2000, declining to nearly 2.0 million by 2025–30, and remaining constant at that level until 2050. The United States is anticipated to increase annually by 1.1 million of these 2 million migrants, more than five times the number expected to be added annually to the next largest recipient, Germany (211,000). The major sending countries are expected to be China, Mexico, India, the Philippines, and Indonesia.

International migration is likely to remain important for specific countries, including the United States. In the mid-1990s, about 125 million people (2% of world population) resided outside of their country of birth or citizenship. In 1990, only 11 countries in the world had more than 2 million migrants, and they collectively had almost 70 million migrants. The largest numbers of migrants were in the United States (19.6 million), India (8.7 million), Pakistan (7.3 million), France (5.9 million), and Germany (5.0 million). The countries with the highest percentage of international migrants in the total population were countries with relatively small populations. In the United Arab Emirates, Andorra, Kuwait, Monaco, and Qatar, 64 to 90% of the population were immigrants.

If predicting international migration is difficult, predicting change in family structure is more difficult. Goldscheider (12) suggested that the fall in fertility during the demographic transition weakened the ties between men.
and women based on parenthood and that the rise in divorce and cohabitation is weakening the ties between fathers and children. Nonmarital births increased as a percentage of all births in the United States from 5.3% in 1960 to 33.0% in 1999. In 1999, the United States had 1.3 million births to unmarried women (13). In 1998, Iceland, Norway, Sweden, Denmark, France, United Kingdom, and Finland all had higher proportions of nonmarital births than the United States. By contrast, in Germany, Italy, Greece, and Japan, less than 15% of births were nonmarital (13). Among United States women aged 15 to 29 years at first birth, when that first birth was conceived before marriage, the fraction who married before the birth fell from 60% in 1960–64 to 23% in 1990–94 (14). By 1994, about 40% of children in the United States did not live with their biological father (12).

In the United States, the number of widowed males aged 55 to 64 per thousand married persons fell from 149 in 1900 to 35 in 2000, whereas the number of divorced males aged 55 to 64 per thousand married persons rose from 7 to 129. Divorced males became more frequent than widowed males between 1970 and 1980. Divorced females became more frequent than widowed females between 1990 and 2000. By 2000, the number of divorced and widowed persons aged 55 to 64 per thousand married persons was 164 males and 426 females (2.6 such females for each such male) (15). Remarriages and stepfamilies are becoming increasingly common.

Three factors set the stage for further major changes in families: fertility falling to very low levels; increasing longevity; and changing mores of marriage, cohabitation, and divorce. In a population with one child per family, no children have siblings. In the next generation, the children of those children have no cousins, aunts, or uncles. If adults live 80 years and bear children between age 20 and 30 on average, then the parents will have decades of life after their children have reached adulthood and their children will have decades of life with elderly parents. The full effects on marriage, child bearing, and child rearing of greater equality between the sexes in education; earnings; and social, legal, and political rights have yet to be felt or understood.

### References and Notes


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### Web Resources

www.sciencemag.org/cgi/content/full/302/5648/1172/DC2

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**Prospects for Biodiversity**

**Martin Jenkins**

Assuming no radical transformation in human behavior, we can expect important changes in biodiversity and ecosystem services by 2050. A considerable number of species extinctions will have taken place. Existing large blocks of tropical forest will be much reduced and fragmented, but temperate forests and some tropical forests will be stable or increasing in area, although the latter will be biotically impoverished. Marine ecosystems will be very different from today’s, with few large marine predators, and freshwater biodiversity will be severely reduced almost everywhere. These changes will not, in themselves, threaten the survival of humans as a species.

What will be the state of the world’s biodiversity in 2050, and what goods and services can we hope to derive from it? First, some assumptions: that the United Nations median population estimate for 2050 holds, so that Earth will have roughly nine billion people—just under half again as many as are currently alive (J., 2); that the Intergovernmental Panel on Climate Change scenarios provide a good indication of global average surface temperatures and atmospheric CO₂ concentrations at that time, with the former ~1°C to 2°C and the latter ~100 to 200 parts per million higher than today (3); and, perhaps most important, although most nebulous, that humanity as a whole has not determined on a radically new way of conducting its affairs. Here, then, is a plausible future.

In this future, the factors that are most directly implicated in changes in biodiversity—habitat conversion, exploitation of wild resources, and the impacts of introduced species (4)—will continue to exert major influences, although their relative importance will vary regionally and across biomes. In combination, they will ensure continuing global biodiversity loss, as expressed through declines in populations of wild species and reduction in area of wild habitats.

### Extinction Rates

To start, as it were, at the end: with extinction, perhaps the most tangible measure of biodiversity loss. The uncertainties that still surround our knowledge of tropical biotas (which include the great majority of extant species); the difficulty of recording extinctions; and our ability, when we put our minds to it, to bring species back from the brink
make it extremely difficult to assess current global extinction rates, let alone estimate future ones. However, an assessment of extinction risk in birds carried out by BirdLife International—using the criteria of IUCN—The World Conservation Union’s Red List of Threatened Species—has concluded (with many caveats) that perhaps 350 species (3.5% of the world’s current avifauna) might be expected to become extinct between now and 2050 (5). Indications are that some other groups—mammals and freshwater fishes, for example—have a higher proportion of species at risk of extinction, although data for these are less complete (4).

Just as it is hard to estimate future extinction rates, so is it difficult to extrapolate forward from current rates of habitat alteration, even where these are known (6). However, some general patterns are clear. With the harvest of marine resources now at or past its peak (7), terrestrial ecosystems will bear most of the burden of having to feed, clothe, and house the expanded human population. This extra burden will fall most heavily on developing countries in the tropics, where the great majority of the world’s terrestrial biological diversity is found.

The Land

Most increased agricultural production is expected to be derived from intensification. However, the Food and Agriculture Organization (FAO) of the United Nations notes that, on the basis of reasonably optimistic assumptions about increasing productivity, at least an extra 120 million ha of agricultural land will still be needed in developing countries by 2030 (8). In a less than wholly efficient world, the amount converted will be much more. Historic precedent and present land availability indicate that almost all new conversion will be in South America and sub-Saharan Africa. More than half the unused suitable cropland is found in just seven countries in these regions: Angola, Argentina, Bolivia, Brazil, Colombia, Democratic Republic of Congo, and Sudan (8). Five of these are among the 25 most biodiverse countries; the exceptions (Angola and Sudan) are both also highly biodiverse (9, 10). Large-scale conversion will continue in most or all of these, with a disproportionately high impact on global biodiversity.

Much conversion here and elsewhere will be of land currently under tropical forest. Fragmentation and loss of such forests will thus continue, albeit overall possibly at a slower rate than at present. The great, largely contiguous forest blocks of Amazonia and the Zaire basin will by 2050 be a thing of the past, with unknown (and hotly debated) impacts on regional weather patterns and global climate. Deforestation pressure will remain high in the immediate future in a number of other tropical developing countries, including those such as Indonesia, Madagascar, and the Philippines, which hold many endemic forest-dependent species, often with small ranges (11, 12). Forest loss here will also have a particularly high impact on biodiversity.

There will, however, still be considerable forest cover in the tropics, much of it in inaccessible or steeply sloping sites unsuitable for clearance and in some protected areas. Even outside such areas, forest cover will be increased in some regions, paralleling the current situation in Northern hemisphere temperate forests (13), because growing urbanization will lead to the abandonment of marginally productive lands (1), allowing reversion to a more natural state. However, uncontrolled and frequent fires will mean that abandoned lands in many areas will remain relatively degraded. In addition, almost all wild lands in the tropics will be impoverished in numbers and diversity of larger animal species, thanks to persistent over-exploitation of wild resources such as bushmeat. Although there have been some local successes, the goal of large-scale sustainable harvest of these resources has so far been elusive and will remain so (14). This means that populations of many species will survive largely or exclusively in heavily managed protected areas.

Although tropical developing countries will continue to suffer quite possibly accelerating biodiversity loss, much less change can be expected in developed temperate countries. Temperate forest cover will continue to increase, or at least stabilize, and many forest species will thrive, although with changes in distribution and relative abundance as a result of climate change. The recent declines in many wild species that are primarily associated with agricultural land (15) may or may not continue. Much will depend on whether the current consumer-led drive to “greener” forms of agriculture has a major long-term impact.

Aquatic Ecosystems

Our most direct and pervasive impact on marine ecosystems and marine biodiversity is through fishing. If present trends (reviewed in detail in (7)) continue, the world’s marine ecosystems in 2050 will look very different from today’s. Large species, and particularly top predators, will be by and large extremely scarce, and some will have disappeared entirely, giving the lie to the old assertion that marine organisms are peculiarly resistant to extinction. Marine ecosystems, particularly coastal ones, will also continue to contend with a wide range of other pressures, including siltation and eutrophication from land runoff, coastal development, conversion for aquaculture, and impacts of climate change (9). Areas of anoxia will increase; most coral reefs will be heavily degraded, but some adaptable species may benefit from warming and may even have started to expand in range.

Available information suggests that freshwater biodiversity has declined as a whole faster than either terrestrial or marine biodiversity over the past 30 years (Fig. 1) (16). The increasing demands that will be placed on freshwater resources in most parts of the world mean that this uneven loss of biodiversity will continue (17). Pollution, siltation, canalization, water abstraction, dam construction, overfishing, and introduced species will all play a part, although their individual impacts will vary regionally. The greatest effects will be on biodiversity in fresh waters in densely populated parts of the tropics, particularly South and Southeast Asia, and in dryland areas, although large-scale hydroengineering projects proposed elsewhere could also have catastrophic impacts (18). Although water quality may stabilize or improve in many inland water systems in developed countries, other factors, such as introduced species, will continue to have an adverse impact on biodiversity in most areas.
How Much Does It Matter?

In assessing the importance of environmental change, we must distinguish between wholesale degradation, such as reduction of a productive, forested slope to bedrock, and reduction in biodiversity per se through the loss of particular populations or species of wild organisms or the replacement of diverse, species-rich systems with less diverse, often intensively managed systems of nonnative species. The former can, of course, have devastating direct consequences for human well-being. It is much more difficult to determine the impacts of the latter. In truth, ecologists and conservationists have struggled to demonstrate the increased material benefits to humans of “intact” wild systems over largely anthropogenic ones. In terms of the most direct benefits, the reverse is indeed obvious—anthropogenic ones. In terms of the most productive, the reverse is indeed obvious—anthropogenic ones. In terms of the most direct benefits, the reverse is indeed obviously the case; this is the logic that has driven us to convert some 1.5 billion ha of land area to intensively managed systems of nonnative species-rich systems with less diverse, often species-poor systems under agriculture. Where increased production of water flow, and soil retention, it seems to be the case; this is the logic that has driven us to convert some 1.5 billion ha of land area to intensively managed systems of nonnative species-rich systems with less diverse, often species-poor systems under agriculture. Where increased production of water flow, and soil retention, it seems to be the case; this is the logic that has driven us to convert some 1.5 billion ha of land area to intensively managed systems of nonnative species-rich systems with less diverse, often species-poor systems under agriculture.

It is much more difficult to determine the impacts of the latter. In truth, ecologists and conservationists have struggled to demonstrate the increased material benefits to humans of “intact” wild systems over largely anthropogenic ones. In terms of the most direct benefits, the reverse is indeed obviously the case; this is the logic that has driven us to convert some 1.5 billion ha of land area to intensively managed systems of nonnative species-rich systems with less diverse, often species-poor systems under agriculture. Even with regard to indirect ecological services, such as carbon sequestration, regulation of water flow, and soil retention, it seems that there are few cases in which these cannot adequately be provided by managed, generally low-diversity systems under agriculture. Even with regard to indirect ecological services, such as carbon sequestration, regulation of water flow, and soil retention, it seems that there are few cases in which these cannot adequately be provided by managed, generally low-diversity systems under agriculture.

Nowhere is this more starkly revealed than in the extinction of species. There is growing consensus that from around 40,000 to 50,000 years ago onward (20), humans have been directly or indirectly responsible for the extinction in many parts of the world of all or most of the larger terrestrial animal species. Although these species were only a small proportion of the total number of species present, they undoubtedly exerted a major ecological influence (21, 22). This means that the “natural” systems we currently think of in these parts of the world (North and South America, Australasia, and virtually all oceanic islands) are nothing of the sort, and yet they still function at least according to our perceptions and over the time scales we are currently capable of measuring. In one well-documented case, New Zealand, a flightless avifauna of at least 38 species has been reduced in a few centuries to 9, most of which are endangered. Here, as David Steadman recently put it, “much of the biodiversity crisis is over. People won: native plants and animals lost” (23). Yet, from a functional perspective, New Zealand shows few signs overall of suffering terminal crisis. There is currently little evidence to dissuade us from the view that what applies for New Zealand today could equally hold, more or less, for the world as a whole tomorrow.

This does not mean, of course, that we can continue to manipulate or abuse the biosphere indefinitely. At some point, some threshold may be crossed, with unforeseeable but probably catastrophic consequences for humans. However, it seems more likely that these consequences would be brought about by other factors, such as abrupt climate shifts (24), albeit ones in which ecosystem changes may have played a part.

References and Notes
15. See, for example, the United Kingdom headline indicators of sustainable development at www.sustainable-development.gov.uk/indicators/headline/index.htm.
Web Resources
www.sciencemag.org/cgi/content/full/302/5648/1175/DC1
www.sciencemag.org/books
Fisheries are commonly perceived as local affairs requiring, in terms of scientific inputs, annual reassessments of species-specific catch quota. Most fisheries scientists are employed by regulatory agencies to generate these quota, which ideally should make fisheries sustainable and profitable, contributors to employment and, through international trade, to global food security.

This perception of fisheries as local and species-specific, managed to directly benefit the fishers themselves, is conducive neither to global predictions nor the collaborative development of long-term scenarios. Indeed, recent accounts of this type, except those of recent accounts of this type, except those of 19th-century notions of inexhaustibility.

The past decade established that fisheries must be viewed as components of a global enterprise, on its way to undermine its supporting ecosystems (6–10).

These developments occur against a backdrop of fishing industry lobbyists arguing that governments drop troublesome regulations and economists assuming that free markets generate inexhaustibility. The aquaculture sector offers to feed the world with farmed fish, while building more coastal feedlots wherein carnivores such as salmon and tuna are fed with other fish (11), the aquatic equivalent of robbing Peter to pay Paul.

The time has come to look at the future of fisheries through (i) identification and extrapolation of fundamental trends and (ii) development and exploration (with or without computer simulation) of possible futures.

The fisheries research community relied, for broad-based analyses, on a data set now shown to be severely biased (10). First-order correction suggests that rather than increasing, as previously reported, global fisheries landings are declining by about 500,000 metric tons per year from a peak of 80 to 85 million tons in the late 1980s. Because overfishing and habitat degradation are likely to continue, extrapolation may be considered (see below). This correction, however, does not consider discarded “by-catch” (about 30% of global landings), only one component of the illegal, unreported, or unregulated (IUU) catches that recently became part of the illegal, unreported, or unregulated (IUU) catches that recently became part of the illegal, unreported, or unregulated (IUU) catches that recently became part of the illegal, unreported, or unregulated (IUU) catches that recently became part of the international fisheries research agenda (12, 13).

The geographic and depth expansion of fisheries is easier to extrapolate (Fig. 1). Over the past 50 years, fisheries targeting benthic and benthic-pelagic organisms have covered the shelves surrounding continents and islands down to 200 m, with increasing inroads below 1000 m, whereas fisheries targeting oceanic tuna, billfishes, and their relatives covered the world ocean by the early 1980s (9). Extrapolating the bottom fisheries trends to 2050 is straightforward (Fig. 1). With satellite positioning and seafloor-imaging systems, we will deplete deep slopes, canyons, seamounts,
and deep-ocean ridges of local accumulations of judiciously renamed bottom fishes, e.g., orange roughy (previously “slimeheads”), Chilean seabass (usually IUU-caught Patagonian toothfish), and hagfish (caught for their “eel-skins,” and here predicted to become a delicacy in trendy restaurants, freshly knotted and sautéed in their own slime), the abyssal tripodfishes being the only group that seems safe so far. Figure 1 also shows the radical trend change required to turn 20% of the shallowest 100 m of the world ocean into marine reserves by 2020, i.e., returning to the 1970s state.

Traditional explanations of overfishing emphasize the open-access nature of the fisheries “commons.” However, overcapitalized fisheries can continue to operate after they have depleted their resource base only through government subsidies (12, 14). Moreover, industrial fisheries depend upon cheap, seemingly superabundant fossil fuels (15), as does agriculture. Thus, we shall here venture a prediction counter to the trends in Fig. 1, based in part on the global oil production trend in Fig. 2A: If fuel energy becomes as scarce and expensive in the next decades as suggested by a number of independent geologists (16), then we should expect the most energy-intensive among industrial fisheries to fold. This would mainly impact deep-sea bottom trawling, which drives the trends in Fig. 1.

One effect may be to increase human consumption of small pelagics (mackerels, herrings, sardines, or anchovies such as the Peruvian anchoveta), now mostly turned into fish meal for agriculture (to grow chickens and pigs, and for use as fertilizer) and aquaculture.

However, predictions are better embedded into scenarios—sets of coherent, plausible stories designed to address complex questions about an uncertain future (17). Scenario analysis is especially important for the fisheries sector, which, although a major provider of food and jobs in many poorer countries, is small relative to the economy of richer countries and is thus “downstream” from most policy decisions.

Pending the detailed analysis of coastal and marine scenarios by the Millennium Ecosystem Assessment (18, 19), we use the four scenarios developed by the United Nations Environment Programme (20) to investigate the future of marine fisheries. For each scenario, we also summarize results of regional simulation models explicitly accounting for interspecies feeding interactions, within a range of ecosystem types and fisheries (21, 22).

1) Markets First, where market considerations shape environmental policy. This may imply the gradual elimination of the subsidies fuelling overfishing (13). Putting markets first may also imply the suppression of IUU fishing (including flags of convenience), which distorts economic rationality as insider trading or fraudulent accounting does. Markets First, by overcoming subsidies, could also lead to the decommissioning of fuel-guzzling distant-water fleets (especially large trawlers), and perhaps lead to a resurgence of small-scale fleets deploying energy-efficient fixed gears. This scenario allows for spontaneous emergence of quasi-marine reserves (i.e., areas not economically fishable, particularly offshore) and thus may reduce the impact on biodiversity. However, high-priced bluefin tuna, groupers, and other taxa (including invertebrates) would remain under pressure.

When modeled, this scenario corresponds to maximizing long-term fisheries “rent” (ex-vessel values of catch minus fishing costs). This usually leads to combinations of fleets exerting about half the present levels of effort, targeting profitable, mostly small, resilient invertebrates and keeping their predators (large fishes) depressed. Shrimp trawlers presently operate in this way, with tremendous ecological impacts on bottom habitats.

2) Security First, where conflicts and inequality lead to strong socioeconomic boundaries between rich and poor. This scenario, although implying some suppression of IUU fishing, would continue “fishing down marine food webs” (6), including in the High Arctic, and subsidization of rich countries’ fleets to their logical ends, including the collapse of traditional fish stocks. This implies development of alternative fisheries targeting jellyfish and other zooplankton (particularly krill) for direct human consumption and as feed for farmed fish. This scenario, generally accentuating present (“south to north”) trading patterns, would largely elimi-

Fig. 1. Fraction of the sea bottom and adjacent waters contributing to the world fisheries from 1950 to 2000 (30) and projected to 2050 by depth (logarithmic scale). Note the strong reversal of trends required for 20% of the waters down to 100-m depth to be protected from fishing by 2020.
nate fish from the markets of countries still “developing” in 2050.

This scenario would also increase exports of polluting technologies to poorer countries, notably coastal aquaculture and/or fertilization of the open sea. This would have negative impacts on the remaining marine fisheries in the host countries, through harmful algal blooms, diseases, and invasive species.

We simulated this scenario through fleet configurations maximizing long-term gross returns to fisheries (i.e., ex-vessel value of landings plus subsidies, without accounting for fishing costs). The results are increasing fishing effort, stagnating or declining catches, and loss of ecosystem components, i.e., a large impact on biodiversity.

3) Policy First, where a range of actions is undertaken by governments to balance social equity and environmental concerns. This is illustrated by the recent Pew Oceans Commission Report (23), which for the United States, proposes a new Department of the Ocean and regional Ecosystem Councils, and a reform of the Fisheries Management Councils, now run by self-interested parties (24).

Similar regulatory reforms, coordinated between countries, combined with marine reserve networks, massive reduction of fishing effort, especially gears that destroy bottom habitat and generate large “by-catch” (25), and abatement of coastal pollution, may bring fisheries back from the brink and reduce the danger of extinction for many species.

This scenario corresponds to simulations where rent is maximized subject to biodiversity constraints. We found no general pattern for the fleet configurations favored under Policy First, because the conceivable policies involve ethical and esthetic values external to the fisheries sector (e.g., shutting down profitable fisheries that kill sea turtles or marine mammals).

4) Sustainability First requires a value system change, favoring environmental sustainability. This scenario, which implies governments’ ratification of and adherence to international fisheries management agreements and bottom-up governance of local resources, would involve creating networks of marine reserves and careful monitoring and rebuilding a number of major stocks (26). This is because high biomasses provide the best safeguard against overestimates of catch quotas and environmental change (11), the latter not covered here but likely to impact future fisheries.

We simulate this scenario by identifying the fishing fleet structure that maximizes the biomass of long-lived organisms in the ecosystem. This requires strong decreases in fishing effort, typically to 20 to 30% of current levels, and a redistribution of remaining effort across trophic levels, from large top predators to small prey species.

These scenarios describe what might happen, not what will come to pass. Still, they can be used to consider what we want for our future. We have noted, however, that many of the fisheries we investigated, e.g., in the North Atlantic (27) or the Gulf of Thailand (28), presently optimize nothing of benefit to society: not rent [taxable through auctions (29)], and not even gross catches (and hence long-term food and employment security). It is doubtful that they will be around in 2050.

References and Notes
1. The FAO regularly issues demand-driven global projections wherein aquaculture, notably in China, is assumed to compensate for shortfalls, if any, in fisheries landings (see www.fao.org).
18. See www.millenniumassessment.org.
21. This work was based on mass-balanced food web models, and their time-dynamic simulation, through coupled differential equations, under the impacts of competing fishing fleets, using the Ecopath with Ecosim software, and models representing the South China Sea (with emphasis on the Gulf of Thailand and Hong Kong waters), the North Atlantic (North Sea, Faroese), the North Pacific (Prince William Sound, Alaska, and Georgia Strait, British Columbia), and other marine ecosystems documented in www.ecopath.org and www.saup.fisheries.ubc.ca/report/report.htm.
27. V. Christensen et al., Fish. Fish. 4, 1 (2003).
30. Disaggregated global landings assembled by the FAO from 1950 to 2000 were used to determine when each 30 min by 30 min spatial cell was first “fished” [i.e., when landings of fish (other than oceanic tuna and billfishes) from that cell first reached 10% of the maximum landings ever reported from that cell]. The percentage of cells fished at each depth was then calculated.
31. D.P., J.A., V.C., and R.W. are members of the Sea Around Us Project, initiated and funded by the Pew Charitable Trusts, Philadelphia. We thank A. Kitchingman and W. Swartz for help with the figures.

Web Resources
www.science.gov/ cgi/content/full/302/5649/1359/DC1
Energy Resources and Global Development

Jeffrey Chow, Raymond J. Kopp, Paul R. Portney

In order to address the economic and environmental consequences of our global energy system, we consider the availability and consumption of energy resources. Problems arise from our dependence on combustible fuels, the environmental risks associated with their extraction, and the environmental damage caused by their emissions. Yet no primary energy source, be it renewable or nonrenewable, is free of environmental or economic limitations.

As developed and developing economies continue to grow, conversion to and adoption of environmentally benign energy technology will depend on political and economic realities.

Energy is the lifeblood of technological and economic development. The energy choices made by the United States and the rest of the world have ramifications for economic growth; the local, national, and global environment; and even the shape of international political alliances and national defense commitments. Countries of varying levels of wealth also face different energy challenges (1). Here, we discuss the availability of global energy resources, how they are used and by whom, and the consequences of the global distribution and use of energy resources.

Although estimates vary, the world’s proved, economically recoverable fossil fuel reserves include almost 1 trillion metric tons of coal, more than 1 trillion barrels of petroleum, and over 150 trillion cubic meters of natural gas (Table 1) (2). In addition to fossil fuels, mineral resources important to energy generation include over 3 million metric tons of uranium reserves (3). To put this into context, consider that the world’s annual 2000 consumption of coal was about 5 billion metric tons or 0.5% of reserves. Natural gas consumption was 1.6% of reserves, whereas oil was almost 3% of reserves, and nuclear electricity generation consumed the equivalent of 2% of uranium reserves (4). Reported recoverable reserves have tended to increase over time, keeping pace with consumption, and now are at or near all-time highs. In relation to current consumption, there remain vast reserves that are adequate for continued worldwide economic development, not even accounting for reserves that will become economically recoverable through continuing discovery and technological advance (5). Thus, it seems that the world is not running out of mineral fuels.

Large fossil fuel reserves are concentrated in a small number of countries, with half of the low-income countries and more than a third of the middle-income countries having no fossil fuel reserves whatsoever (6). If energy reserves were necessary for economic development, several of the world’s poorest nations would be disadvantaged. However, many energy-bereft countries (such as Japan) have become highly developed through sufficient access to international energy markets. Conversely, Nigeria possesses substantial reserves but remains one of the poorest countries, its energy production activities mired in corruption. Thus, simply possessing large fossil energy reserves is of questionable value to a country’s development if there is no well-functioning and adequately equitable socioeconomic system enabling it to extract and deploy those energy resources for their full social benefit.

Total global energy use exceeds 370 exajoules (EJ) [350 quadrillion British thermal units (Btus)] per year, which is equivalent to over 170 million barrels of oil each day (7). Approximately 95% of this energy comes from fossil fuels. Global energy consumption draws from six primary sources: 44% petroleum, 26% natural gas, 25% coal, 2.5% hydroelectric power, 2.4% nuclear power, and 0.2% nonhydro renewable energy (8, 9). A considerable amount of primary energy is converted to electricity either in the course of initial harvesting (as for hydroelectric, wind, and geothermal) or by combustion (as for fossil, biomass, and waste fuels). These estimates do not include nonmarket fuelwood and farm residues that are prevalent in many developing countries, because global estimates of noncommercial energy use are often incomplete and unreliable. However, the International Energy Agency (IEA) suggests that biomass provides on average one-third of the energy needs in Africa, Asia, and Latin America, and as much as 80 to 90% in the poorest countries of these regions (10).

Processing and conversion of primary sources permit enormous versatility in energy use. The end applications of this consumption can be categorized into five major sectors: industry, transportation, agriculture, commercial and public services, and residential (11). Developing countries use the most energy in the residential sector (12), followed by industrial and then transportation (Fig. 1A). The opposite is true for developed countries, where transportation consumes the largest amount of energy, followed by industrial and then residential consumption (Fig. 1B).

Unsurprisingly, the developing and industrialized worlds demonstrate striking disparities in annual energy consumption per capita (13). Industrialized country energy use exceeds that of the developing countries for all five end-use sectors by 3 to 14 times, depending on the sector (Fig. 1, A and B) (14). In aggregate, the average person in the developing countries consumes the equivalent of 6...
Table 1. Proved reserves of mineral energy resources, their approximate energy content, and their distribution among income groups in 2001. Petroleum, coal, and natural gas estimates are calculated from data in (29, 32). Uranium estimates are calculated from data in (30).

<table>
<thead>
<tr>
<th>Income group</th>
<th>Petroleum (10^9 barrels)</th>
<th>Coal (10^6 metric tons)</th>
<th>Natural gas (10^12 cubic m)</th>
<th>Uranium (metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poorest 10%</td>
<td>24</td>
<td>140</td>
<td>2.33</td>
<td>475.4</td>
</tr>
<tr>
<td>Low-income</td>
<td>49.5</td>
<td>290</td>
<td>10</td>
<td>0.05</td>
</tr>
<tr>
<td>Middle-income</td>
<td>723.6</td>
<td>4300</td>
<td>70.14</td>
<td>8800</td>
</tr>
<tr>
<td>Low- + middle-income (developing)</td>
<td>773.1</td>
<td>4500</td>
<td>74.93</td>
<td>11000</td>
</tr>
<tr>
<td>High-income (developed)</td>
<td>258.6</td>
<td>1500</td>
<td>25.07</td>
<td>8200</td>
</tr>
<tr>
<td>Richest 10%</td>
<td>38.6</td>
<td>230</td>
<td>3.74</td>
<td>317104.1</td>
</tr>
<tr>
<td>Total</td>
<td>1031.7</td>
<td>6100</td>
<td>82.77</td>
<td>32761.2</td>
</tr>
</tbody>
</table>

*EJ = exajoules = 10^18 joules (9.48 × 10^14 Btus). †Proved reserves of uranium refer to RARs described by the International Atomic Energy Agency.

barrels of oil [34 gigajoules (GJ) or 32 million Btus] annually, whereas the average person in the developed world consumes nearly 40 barrels (220 GJ or 210 million Btus) (table S1) (15). Residents of the poorest 10% of countries consume less than one barrel of oil equivalent per year per capita, whereas their counterparts in the richest 10% of countries consume over 60 times as much. Also striking are disparities within the developing world. On an annual per-capita basis, the middle-income countries use four times as much energy as their low-income counterparts.

These relationships between wealth and energy consumption suggest that as a country becomes richer, its people tend to consume substantially more energy (table S1). However, looking at energy use within the high-income group alone, the correlation is weaker. For example, Norway has a gross national income per capita (GNI/pop) of U.S. $34,530 and Japan is slightly higher at U.S. $35,620, but energy consumption per capita is lower in Japan: 150 GJ compared to 250 GJ for Norway. This discrepancy is probably due to the availability of relatively inexpensive hydroelectric power in Norway, whereas Japan, possessing fewer local resources, has greater incentives to be more energy efficient. Therefore, although at a coarse scale energy consumption per capita increases with economic growth, there are different paths that a particular country’s energy system can take in its development, with some paths resulting in greater efficiency and less consumption than others.

Moreover, when one examines energy use per dollar of gross domestic product (GDP), the low-income countries use more energy to create a dollar of GDP than do the high-income countries, because of greater use of more energy-efficient technologies as a country develops (table S1) (16). Furthermore, as cleaner energy-efficient technologies generated by the industrialized countries become cheaper, the growing economies of the developing world become more likely to adopt them, bypassing more wasteful and polluting technologies. For example, countries such as China, India, Brazil, and the Philippines have been installing high-voltage direct-current cables to deliver electricity with greater reliability and efficiency than the alternating-current cables prevalent in the United States.

The data also strongly indicate that the world is heavily dependent on fossil fuel energy, with only about 5% coming from other sources, and it will remain so barring substantial technological change. In the near term, this continued dependence is partially due to the paucity of convenient alternatives to petroleum products as fuels in the transportation sector, which consumes more energy in the developed world. Currently, transportation in the poorest decile of countries consumes less than 3% of the energy consumed by that sector in the richest countries. As developing countries become richer and expand their transportation networks, petroleum products will likely fuel them. The industrial sector of the developed world also relies heavily on fossil fuels. Institutional inertia, as well as the cost of replacing capital-intensive, fossil energy–dependent infrastructure, slow the pace at which nonfossil substitutions can occur.

Between 1980 and 2001, worldwide consumption of petroleum, coal, and natural gas increased by 22, 27, and 71%, respectively. Concurrently, annual world carbon dioxide (CO2) emissions from the consumption and flaring of fossil fuels, implicated as the predominant cause of global climate change, increased from 5 billion to 6.6 billion metric tons carbon equivalent, with relatively steady increases occurring for all income groups (fig. S1). Fossil fuel consumption also results in lesser emissions of other greenhouse gases (GHGs), such as carbon monoxide, methane, and volatile organic compounds (VOCs), not to mention nitrous oxides (NOx) that facilitate the formation of heat-trapping tropospheric ozone. Although fossil fuel reserves are in no danger of diminishing in the foreseeable future, should the world continue to consume all or even a large fraction of those

![Fig. 1. Per-capita energy consumption by sectoral end use in (A) the developing world and (B) the developed world (in gigajoules)](image_url)
resources though normal combustion processes, the release of additional GHGs into the atmosphere would likely have substantial consequences for the global climate. According to the Intergovernmental Panel on Climate Change (IPCC), climate models generally predict that continued emissions of anthropogenic GHGs beyond the sequestration capacity of natural sinks will result in not only increased mean temperatures but also more frequent extreme climate events such as droughts and intense storms, with significant consequences for ecosystems, agricultural productivity, and human welfare (17).

Besides GHG emissions, fossil fuel production and use come with other environmental costs. Fossil fuel exploration requires seismic testing and road building that can harm wildlife and fragment habitats. Extraction requires the replacement of natural habitat with infrastructure and can lead to leaking of fuels and toxic byproducts, such as arsenic, cadmium, and mercury, into the local environment.

In the case of oil, spills that occur during transportation and refining also damage local environments. Sulfur dioxide, NOX, and VOCs released from coal and petroleum combustion cause a myriad of environmental problems, including acid rain, smog, and nitrogen loading.

Furthermore, the traditional alternatives to fossil energy—hydroelectricity and nuclear power—have environmental and social costs that limit their viability as long-term fossil fuel substitutes. In addition to the drawback of being near saturation, hydroelectric power infrastructure causes dramatic alterations in riparian ecosystems and often the inundation of human settlements and terrestrial habitat. Fissile nuclear power, too, is unlikely to expand because of objections to waste disposal and concerns over weapons proliferation.

It should be noted that no primary energy source and its associated technology are completely free of environmental and other drawbacks. Wind-powered electric turbines require the installation of infrastructure, can cause the death of migratory birds, and elicit local objections on aesthetic grounds. Geothermal plants emit CO2 and hydrogen sulfide. Wind, solar, and geothermal systems are capital-intensive and their viability is graphically limited (18). Without affordable and practical electricity storage, intermittency is also a problem for wind and solar power. The domestically combusted biomass used in developing countries is often a health hazard because of indoor smoke inhalation (19), and mass-produced fuels derived from biomass place greater burdens on agricultural and forest productivity. Even the highly touted hydrogen fuel cell, which releases only water vapor, would initially require fossil fuels as hydrogen fuel stock (20). In order to minimize environmental damage relative to the benefits of energy consumption, a sustainable, environmentally benign energy system, or at least the transition to one, will involve a heterogeneous portfolio of renewable primary sources in order to minimize the environmental impact of any particular source.

The environmental costs of fossil, hydroelectric, and nuclear energy consumption could drive the world toward alternative sources before scarcity becomes a significant issue. Government programs to reduce the negative environmental impacts of fossil fuel production and consumption have the same effect as scarcity-induced price increases, and would stimulate (or mandate) new energy technologies that increase efficiency, mitigate pollution, and substitute for fossil energy. Policy mechanisms to achieve these ends include environmental standards, fuel and emission taxes, subsidies for renewable energy production, mandated diversified energy portfolios, and emission permit–trading schemes. In the United States and elsewhere, several of these policies (such as regulated limits, emission fees, and tradable permits) have been successfully implemented to reduce noncarbon air pollution, improve air quality, and reduce acid rain (21–24).

Given growing environmental concerns, the future use of fossil resources will likely not follow the standard combustion path of the past but will involve processes with increased efficiency, lower localized air pollution, and perhaps carbon capture and sequestration before, after, or instead of combustion (25). Electricity in particular will remain the most important end-use energy form because of its flexibility in both generation and use. Renewable sources of electricity from solar, wind, geothermal, and tidal power are currently available, but they remain the least consumed form of energy across all income groups (26). Per-capita consumption rates do not exceed 1 MJ (100,000 Btu) per year in the developing-country categories (less than a gallon of oil equivalent), and do not exceed 1 GJ (1 million Btu) per year in the high-income category, with only 24 industrialized countries consuming significant amounts (27).

Renewable energy sources will become prevalent only if they can be more competitive than fossil fuels in terms of relative prices (Table 2). Competition from lower-cost conventional power production, notably by gas turbine combined cycle (GTCC) systems, will continue to undercut renewables, even with falling costs (28). Rather than wait for scarcity-induced price rises, governments can accelerate the adoption of renewables with two coordinated and self-reinforcing actions. First, governments can adopt a variety of R&D policies (usually in the form of subsidies) that would bring down the price and improve the performance of renewables in comparison with fossil fuels. Second, they can raise the price of fossil fuels through carbon taxes or permits and thereby tilt the economics toward renewables. These actions serve to push renewables forward by subsidizing their development, while at the same time pulling renewables into the market by disadvantaging the price competitiveness of fossil fuels.

As the recent blackouts in North America and Italy made clear, even energy systems in the richest countries are far from problem-free. Similar systems in the developing world may be even more trouble-prone as they develop. However, sub-Saharan Africa and other poor countries will probably never have an electricity grid exactly like those of today’s high-income countries, even when they have pulled themselves out of wrenching poverty.

In the same way that the developing world is bypassing the paired-copper-wire grid that characterizes telephony in the developed world and is leapfrogging to cellular communication, so too is it likely to rely much less heavily on our technological model of electricity generation. Rather than adopting a system with large central-station power plants generating electricity and distributing it over long distances, we speculate that the developing countries, especially the poorest, are more likely to
eventually adopt smaller and less capital-intensive microturbines and renewable sources of electricity generation such as biomass, wind, and solar that are closer to the point of use. These applications will bring with them their own sets of problems, but will enable the developing world to avoid others.

Will the world make a transition to alternative, more renewable sources of energy? The simple answer is yes, if only because, in time, supplies of fossil fuels will become too costly. For the next 25 to 50 years, however, this seems not to be a likely prospect. With energy choices driven by relative prices, fossil fuels will dominate energy use for many years to come. These fuels remain relatively inexpensive, and they are supported by a very broad and long-lived infrastructure of mines, wells, pipelines, refineries, gas stations, power plants, rail lines, tankers, and vehicles. Very powerful political constituencies exist worldwide to ensure that investments in this infrastructure are protected.

If fossil fuel depletion occurs more rapidly than we expect, or if governments enact policies that artificially increase fossil fuel prices, renewables and alternative energy sources may come online more quickly. The requisite political will and financial support to enact such changes will occur only when societies and their governments decide that the benefits of fossil fuel consumption do not make up for the negative effects on environmental health and human welfare of fossil fuel dependence.

References and Notes

1. We analyzed year 2000 data from 211 countries, using the World Bank’s method of distinguishing between low-, middle-, and high-income countries according to GNI/pop. We refer to low- and middle-income countries jointly as developing countries, and high-income countries are considered industrialized or developed countries. Of the countries considered in this analysis, approximately 75% fall into the former category. Countries are low-income if GNI/pop is less than U.S. $750 (69 countries, including the Congo, India, and Indonesia); middle-income if GNI/pop is between U.S. $750 and $9250 (85 countries, including Argentina, Mexico, and Turkey); or high-income if GNI/pop is greater than U.S. $9250 (57 countries, including the United States, Japan, and Western Europe). We have also identified those countries comprising the poorest 10% (such as Cambodia, Chad, and Tajikistan) and the richest 10% (such as the United States, Singapore, and the United Kingdom). The developing-country group is heterogeneous in resource endowments and development conditions; whereas classification as a developed country does not imply a preferred or final stage of development, GNI/pop is a convenient criterion among many metrics for the development stage of a country, but not necessarily reflect development status. GNI, GDP, and population data for 2000 are drawn from the World Development Indicators 2002, published by the World Bank. Population, GNI/pop, and income categorization for all 211 countries are available at [31].

2. These numbers are based on year 2001 data from [29]. Reserves include only resources that are identified as economically and technically recoverable with current technologies and prices. Other resources with foreseeable or unknown potential for recovery exist but are not included in this report, because estimates are often highly speculative and unreliable, particularly estimates of resources in developing countries. Reserve estimates tend to expand over time, as technology increases the number of economically recoverable reserves. These numbers are based on year 2001 data from [30]. This estimate includes reasonably assured resources (RARs) identified by the IAEA and does not include other potential resources and secondary supplies from reprocessed uranium, reenriched uranium, and highly enriched uranium from the dismantlement of nuclear weapons. A list of reserves by country is available at [31].

3. However, 42% of uranium used for nuclear electricity generation is currently supplied by secondary sources, so the actual consumption of uranium reserves is less than this estimate suggests.

4. It should be noted that the three major fossil fuels are not perfect substitutes for each other, particularly in the short term. Petroleum derivatives offer versatility in use and ease of transport that make them ideal fuels for the transportation sector. Coal is the most abundant fossil fuel but generates the most airborne pollutants. Hence, coal-fired electricity generation plants are gradually giving way to gas-fired plants. Natural gas is the cleanest-burning and most energy-efficient fossil fuel, but supply is currently hindered by insufficient transport and storage infrastructure, such as regasification and storage facilities for importing liquefied natural gas from overseas.

5. Similarly, the majority of reserves in the developed countries also are concentrated in a relatively few nations, notably the United States and several of the wealthier oil-producing Middle Eastern states. A map and list of global reserves by country as well as a more detailed descriptive analysis are available at [31].

6. These numbers are based on year 2000 data from [29].

8. Renewables include energy generated from sources such as geothermal, wind, solar, wood, and waste fuels. This includes the domestic use of fuelwood and other biomass common in developing countries, but does include energy derived from electric power generation using these fuels.

9. Global maps and tables of consumption by energy source are available at [31].

10. S. L. D’Apoite, in Biomass Energy: Data, Analysis and Energy Balances of the OECD Countries and Energy Balances of the Non-OECD Countries, compiled by the International Energy Agency. These data exist only for 133 countries and are not directly comparable to the data discussed above for 200-plus countries provided by the Energy Information Administration (EIA) of the U.S. Department of Energy. This data set includes the consumption of combustible renewables and waste, such as fuelwood, whereas the EIA data set does not. Interdirect comparison of the two different sets of data and analyses would not be robust. More detailed descriptions of end-use sectors as defined by the International Energy Agency are available at [31].

12. Residential energy consumption in many regions that are included among the developing states consists predominantly of combustible materials and waste such as fuelwood, manure, and other biofuels, rather than the forms of energy described in the analyses above. Biomass is often the only available and affordable source of energy for basic needs, such as cooking and heating, for large portions of rural populations and for the poorest sections of urban populations in developing countries.

13. Maps and tables of per-capita aggregate energy consumption by country are available at [31].

14. Country tables of per-capita energy consumption by end use are available at [31].

15. These numbers are based on year 2000 data from [29]. Per-capita consumption is calculated by dividing aggregate energy consumption by population and does not account for imports and exports of energy embodied in the trade of goods.

16. It is generally accepted practice to use GDP rather than GNI when discussing the energy intensity of economic output. Our conclusions would be no different if we used GNI. Global maps and tables of aggregate energy consumption per dollar of GDP are available at [31].


18. Coastal areas and plains are ideal for wind power, sunny areas such as equatorial regions for solar power, and volcanic basins for geothermal.

19. These fuels are also often used inefficiently because of poor technology (such as a lack of closed stoves or ventilation) and have negative health effects, depending on their method of use. Thus, the health hazards associated with traditional biomass are partly the consequence of sociocultural and development programs and can be mitigated with simple technological improvements.

20. In the case of hydrogen fuel cells, one must also consider the environmental consequences of increased levels of water vapor in the atmosphere, should this technology be widespread in the future.


26. Renewables referred to in this discussion include electricity generated from geothermal, solar, wind, biomass, and waste sources, but not domestically combusted fuels.

27. These numbers are based on year 2000 data from [29].


31. See www.rrf.org/energyreserves/.
Modern Global Climate Change

Thomas R. Karl1 and Kevin E. Trenberth2

Modern climate change is dominated by human influences, which are now large enough to exceed the bounds of natural variability. The main source of global climate change is human-induced changes in atmospheric composition. These perturbations primarily result from emissions associated with energy use, but on local and regional scales, urbanization and land use changes are also important. Although there has been progress in monitoring and understanding climate change, there remain many scientific, technical, and institutional impediments to precisely planning for, adapting to, and mitigating the effects of climate change. There is still considerable uncertainty about the rates of change that can be expected, but it is clear that these changes will be increasingly manifested in important and tangible ways, such as changes in extremes of temperature and precipitation, decreases in seasonal and perennial snow and ice extent, and sea level rise. Anthropogenic climate change is now likely to continue for many centuries. We are venturing into the unknown with climate, and its associated impacts could be quite disruptive.

The atmosphere is a global common that responds to many types of emissions into it, as well as to changes in the surface beneath it. As human balloon flights around the world illustrate, the air over a specific location is typically halfway around the world a week later, making climate change a truly global issue.
reflected by clouds and from the surface. The rest (120 PW) is absorbed by the atmosphere, land, or ocean and ultimately emitted back to space as infrared radiation (1). Over the past century, infrequent volcanic eruptions of gases and debris into the atmosphere have significantly perturbed these energy flows; however, the resulting cooling has lasted for only a few years (2). Inferred changes in total solar irradiance appear to have increased global mean temperatures by perhaps as much as 0.2°C in the first half of the 20th century, but measured changes in the past 25 years are small (2). Over the past 50 years, human influences have been the dominant detectable influence on climate change (2). The following briefly describes the human influences on climate, the resulting temperature and precipitation changes, the time scale of responses, some important processes involved, the use of climate models for assessing the past and making projections into the future, and the need for better observational and information systems.

The main way in which humans alter global climate is by interference with the natural flows of energy through changes in atmospheric composition, not by the actual generation of heat in energy usage. On a global scale, even a 1% change in the energy flows, which is the order of the estimated change to date (2), dominates all other direct influences humans have on climate. For example, an energy output of just one PW is equivalent to that of a million power stations of 1000-MW capacity, among the largest in the world. Total human energy use is about a factor of 9000 less than the natural flow (3).

Global changes in atmospheric composition occur from anthropogenic emissions of greenhouse gases, such as carbon dioxide that results from the burning of fossil fuels and methane and nitrous oxide from multiple human activities. Because these gases have long (decades to centuries) atmospheric lifetimes, the result is an accumulation in the atmosphere and a build-up in concentrations that are clearly shown both by instrumental observations of air samples since 1958 and in bubbles of air trapped in ice cores before then. Moreover, these gases are well distributed in the atmosphere across the globe, simplifying a global monitoring strategy. Carbon dioxide has increased 31% since preindustrial times, from 280 parts per million by volume (ppmv) to more than 370 ppmv today, and half of the increase has been since 1965 (4) (Fig. 1). The greenhouse gases trap outgoing radiation from the Earth to space, creating a warming of the planet.

Emissions into the atmosphere from fuel burning further result in gases that are oxidized to become highly reflective micron-sized aerosols, such as sulfate, and strongly absorbing aerosols, such as black carbon or soot. Aerosols are rapidly (within a week or less) removed from the atmosphere through the natural hydrological cycle and dry deposition as they travel away from their source. Nonetheless, atmospheric concentrations can substantially exceed background conditions in large areas around and downwind of the emission sources. Depending on their reflectivity and absorption properties, geometry and size distribution, and interactions with clouds and moisture, these particulates can lead to either net cooling, as for sulfate aerosols, or net heating, as for black carbon. Importantly, sulfate aerosols affect climate directly by reflecting solar radiation and indirectly by changing the reflective properties of clouds and their lifetimes. Understanding their precise impact has been hampered by our inability to measure these aerosols directly, as well as by their spatial inhomogeneity and rapid changes in time. Large-scale measurements of aerosol patterns have been inferred through emission data, special field experiments, and indirect measurements such as sun photometers (5).

Human activities also have a large-scale impact on the land surface. Changes in land-use through urbanization and agricultural practices, although not global, are often most pronounced where people live, work, and grow food, and are part of the human impact on climate (6, 7). Large-scale deforestation and desertification in Amazonia and the Sahel, respectively, are two instances where evidence suggests there is likely to be human influence on regional climate (8–10). In general, city climates differ from those in surrounding rural green areas, because of the “concrete jungle” and its effects on heat retention, runoff, and pollution, resulting in urban heat islands.

There is no doubt that the composition of the atmosphere is changing because of human activities, and today greenhouse gases are the largest human influence on global climate (2). Recent greenhouse gas emission trends in the United States are upward (11), as are global emissions trends, with increases between 0.5 and 1% per year over the past few decades (12). Concentrations of both reflective and nonreflective aerosols are also estimated to be increasing (2). Because radiative forcing from greenhouse gases dominates over the net cooling forcings from aerosols (2), the popular term for the human influence on global climate is “global warming,” although it really means global heating, of which the observed global temperature increase is only one consequence (13) (Fig. 1). Already it is estimated that the Earth’s climate has exceeded the bounds of natural variability (2), and this has been the case since about 1980.

Surface moisture, if available (as it always is over the oceans), effectively acts as the “air conditioner” of the surface, as heat used for evaporation moistens the air rather than warming it. Therefore, another consequence of global heating of the lower troposphere is accelerated land-surface drying and more atmospheric water vapor (the dominant greenhouse gas). Accelerated drying increases the incidence and severity of droughts, whereas additional atmospheric water vapor increases the risk of heavy precipitation events (14). Basic theory (15), climate model simulations (2), and empirical evidence (Fig. 2) all confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events even when the total precipitation remains constant, and with prospects for

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**Fig. 1.** Time series of departures from the 1961 to 1990 base period for an annual mean global temperature of 14.0°C (bars) and for a carbon dioxide mean of 334 ppmv (solid curve) during the base period, using data from ice cores and (after 1958) from Mauna Loa (4). The global average surface heating approximates that of carbon dioxide increases, because of the cancellation of aerosols and other greenhouse gas effects, but this does not apply regionally (2). Many other factors (such as the effects of volcanic eruptions and solar irradiance changes) are also important.
even stronger events when precipitation amounts increase (16–18).

There is considerable uncertainty as to exactly how anthropogenic global heating will affect the climate system, how long it will last, and how large the effects will be. Climate has varied naturally in the past, but today’s circumstances are unique because of human influences on atmospheric composition. As we progress into the future, the magnitude of the present anthropogenic change will become overwhelmingly large compared to that of natural changes. In the absence of climate mitigation policies, the 90% probability interval for warming from 1990 to 2100 is 1.7° to 4.9°C (19). About half of this range is due to uncertainty in future emissions and about half is due to uncertainties in climate models (2, 19), especially in their sensitivity to forcings that are complicated by feedbacks, discussed below, and in their rate of heat uptake by the oceans (20). Even with these uncertainties, the likely outcome is more frequent heat waves, droughts, extreme precipitation events, and related impacts (such as wild fires, heat stress, vegetation changes, and sea level rise) that will be regionally dependent.

The rate of human-induced climate change is projected to be much faster than most natural processes, certainly those prevailing over the past 10,000 years (2). Thresholds likely exist that, if crossed, could abruptly and perhaps almost irreversibly switch the climate to a different regime. Such rapid change is evident in past climates during a slow change in the Earth’s orbit and tilt, such as the Younger Dryas cold event from ~11,500 to ~12,700 years ago (2), perhaps caused by freshwater discharges from melting ice sheets into the North Atlantic Ocean and a change in the ocean thermohaline circulation (21, 22). The great ice sheets of Greenland and Antarctica may not be stable, because the extent to which cold-season heavier snowfall partially offsets increased melting as the climate warms remains uncertain. A combination of ocean temperature increases and ice sheet melting could systematically inundate the world’s coasts by raising sea level for centuries.

Given what has happened to date and as projected in the future (2), substantial further climate change is guaranteed. The rate of change can be slowed, but it is unlikely to be stopped in the 21st century (23). Because concentrations of long-lived greenhouse gases are dominated by accumulated past emissions, it takes many decades for any change in emissions to have much effect. This means the atmosphere still has unrealized warming (estimated to be at least another 0.5°C) and that sea level rise may continue for centuries after an abatement of anthropogenic greenhouse gas emissions and the stabilization of greenhouse gas concentrations in the atmosphere.

Our understanding of the climate system is complicated by feedbacks that either amplify or damp perturbations, the most important of which involve water in various phases. As temperatures increase, the water-holding capacity of the atmosphere increases along with water vapor amounts, producing water vapor feedback. As water vapor is a strong greenhouse gas, this diminishes the loss of energy through infrared radiation to space. Currently, water vapor feedback is estimated to contribute a radiative effect from one to two times the size of the direct effect of amount can cause either warming or cooling. Future changes in clouds are the single biggest source of uncertainty in climate predictions. They contribute to an uncertainty in the sensitivity of models to changes in greenhouse gases, ranging from a small negative feedback, thereby slightly reducing the direct radiative effects of increases in greenhouse gases, to a doubling of the direct radiative effect of increases in greenhouse gases (25). Clouds and precipitation processes cannot be resolved in climate models and have to be parametrically represented (parameterized) in terms of variables that are resolved. This will continue for some time into the future, even with projected increases in computational capability (26).

Ice-albedo feedback occurs as increased warming diminishes snow and ice cover, making the planet darker and more receptive to absorbing incoming solar radiation, causing warming, which further melts snow and ice. This effect is greatest at high latitudes. Decreased snow cover extent has significantly contributed to the earlier onset of spring in the past few decades over northern-hemisphere high latitudes (27). Ice-albedo feedback is affected by changes in clouds, thus complicating the net feedback effect.

The primary tools for predicting future climate are global climate models, which are fully coupled, mathematical, computer-based models of the physics, chemistry, and biology of the atmosphere, land surface, oceans, and cryosphere and their interactions with each other and with the sun and other influences (such as volcanic eruptions). Outstanding issues in modeling include specifying forcings of the climate system; properly dealing with complex feedback processes (Fig. 3) that affect carbon, energy, and water sources, sinks and transports; and improving simulations of regional weather, especially extreme events. Today’s inadequate or incomplete measurements of various forcings, with the exception of well-mixed greenhouse gases, add uncertainty when trying to simulate past and present climate. Confidence in our ability to predict future climate is dependent on our ability to use climate models to attribute past and present climate change to specific forcings. Through clever use of paleoclimate data, our ability to reconstruct past forcings should improve, but it is unlikely to provide the regional detail neces-

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Fig. 2. Climatological of the intensity of daily precipitation as a percentage of total amount in 10 mm/day categories for different temperature regimes, based on 51, 37, and 12 worldwide stations, respectively: blue bars, −3°C to 19°C; pink bars, 19°C to 29°C; dark red bars, 29°C to 35°C.

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nary that comes from long-term direct measurements. An example of forcing uncertainty comes from recent satellite observations and data analyses of 20th-century surface, upper air, and ocean temperatures, which indicate that estimates of the indirect effects of sulfate aerosols on clouds may be high, perhaps by as much as a factor of two (27–29). Human behavior, technological change, and the rate of population growth also affect future emissions and our ability to predict these must be factored into any long-term climate projection.

Regional predictions are needed for improving assessments of vulnerability to and impacts of change. The coupled atmosphere-ocean system has a preferred mode of behavior known as El Niño, and similarly the atmosphere is known to have preferred patterns of behavior, such as the North Atlantic Oscillation (NAO). So how will El Niño and the NAO change as the climate changes? There is evidence that the NAO, which affects the severity of winter temperatures and precipitation in Europe and eastern North America, and El Niño, which has large regional effects around the world, are behaving in unusual ways that appear to be linked to global heating (2, 31–33). Hence, it is necessary to be able to predict the statistics of the NAO and El Niño to make reliable regional climate projections.

Ensembles of model predictions have to be run to generate probabilities and address the chaotic aspects of weather and climate. This can be addressed in principle with adequate computing power, a challenge in itself. However, improving models to a point where they are more reliable and have sufficient resolution to be properly able to represent known important processes also requires the right observations, understanding, and insights (brain power). Global climate models will need to better integrate the biological, chemical, and physical components of the Earth system (Fig. 3). Even more challenging is the seamless flow of data and information among observing systems, Earth system models, socioeconomic models, and models that address managed and unmanaged ecosystems. Progress here is dependent on overcoming not only scientific and technical issues but also major institutional and international obstacles related to the free flow of climate-related data and information.

In large part, reduction in uncertainty about future climate change will be driven by studies of climate change assessment and attribution. Along with climate model simulations of past climates, this requires comprehensive and long-term climate-related data sets and observing systems that deliver data free of time-dependent biases. These observations would ensure that model simulations are evaluated on the basis of actual changes in the climate system and not on artifacts of changes in observing system technology or analysis methods (34). The recent controversy regarding the effects that changes in observing systems have had on the rate of surface versus tropospheric warming (35, 36) highlights this issue. Global monitoring through space-based and surface-based systems is an international matter, much like global climate change. There are encouraging signs, such as the adoption in 1999 of a set of climate monitoring principles (37), but these principles are impotent without implementation. International implementation of these principles is spotty at best (38).

We are entering the unknown with our climate. We need a global climate observing system, but only parts of it exist. We must not only take the vital signs of the planet but also assess why they are fluctuating and changing. Consequently, the system must embrace comprehensive analysis and assessment as integral components on an ongoing basis, as well as innovative research to better interpret results and improve our diagnostic capabilities. Projections into the future are part of such activity, and all aspects of an Earth information system feed into planning for the future, whether by planned adaptation or mitigation. Climate change is truly a global issue, one that may prove to be humanity’s greatest challenge. It is very unlikely to be adequately addressed without greatly improved international cooperation and action.

References and Notes

15. The Clausius Clapeyron equation governs the water-holding capacity of the atmosphere, which increases by ~7% per degree Celsius increase in temperature (13).
30. J. Coakley Jr., personal communication.
35. The Climate Change Science Program plan is available at www.climatescience.gov.
37. The climate principles were adopted by the Subsidiary Body on Science, Technology and Assessment of the United Nations Framework Convention on Climate Change (UNFCCC).
39. We thank A. Leetmaa, J. Hurrell, J. Mahlman, and R. Cicerone for helpful comments, and J. Enloe for providing the calculations for Fig. 2. This article reflects the views of the authors and does not reflect government policy. The National Climatic Data Center is part of NOAA’s Satellite and Information Services. The National Center for Atmospheric Research is sponsored by the NSF.
Web Resources
www.sciencemag.org/cgi/content/full/302/5651/1719/DC1
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T he past four issues of *Science* have examined the State of the Planet, with particular emphasis on global commons—broadly speaking, those critical resources we all must share. Climate, soil, air, water, energy resources, food, fisheries, and biodiversity are all elements of the global commons, and all have prospects that range from uncertain to perilous.

In his influential *Science* essay 35 years ago, Garrett Hardin suggested that humankind was doomed to overexploit the commons unless the freedom to breed was relinquished. Hardin’s position was perceived as a simple choice between two coercive alternatives for managing the commons: centralized government and institutionalized private property.

Our special issue begins with an overview by Dietz, Ostrom, and Stern (p. 1907) of progress toward alternatives to the stark choice posed by Hardin. They conclude, with cautious optimism, that experience of the past 35 years has shown that paths to adaptive governance can indeed be opened, but not without a struggle. Aspects of this struggle are explored in the articles that follow.

Several Viewpoints discuss communication and discourse within and between institutions and disciplines concerned with the management of common resources. McMichael et al. (p. 1919) highlight the need for demography, economics, ecology, and epidemiology to talk to each other more effectively. Houck (p. 1926) explores the uneasy relationship between science and law in U.S. environmental policy during the decades since Hardin’s article. Adams et al. (p. 1915) point out that disparities in the perceptions, knowledge, and beliefs of different stakeholders present barriers to effective communication between stakeholders in the management of common-pool resources, and that recognition of this problem by all protagonists is an important step on the road to policy-making. The notion of social capital, which stresses the relationship between sustainability and social norms, provides a potential escape from Hardin’s solutions to tragedy: Pretty (p. 1912) provides an account of the positive outcomes that can ensue, at least at the local and regional level, when communities are able to adopt such an approach.

The remaining Viewpoints examine three of the global commons: climate, food, and health. All of these are areas where the concept of social capital needs to be scaled up from local to international, and ultimately global, and where science has a partnership with policy-making. Chronic and infectious diseases are inimical to progress toward more sustainable lifestyles; Mascie-Taylor and Karim (p. 1921) discuss the scale of the global health problem and outline solutions on a scale that extends from local to global. Rosegrant and Cline (p. 1917) show that food security in the coming years depends not just on agricultural research and improvement, but on a web of other factors from education to investment in ecosystem services. Finally, Watson (p. 1925) and Hasselmann et al. (p. 1923) explore the political challenges posed by global climate change, arguably the single most pressing global environmental problem.

Hardin suggested that the tragedy of the commons belonged to a class of problems that have no technical solution, effectively denying a role for science. However, as the articles in this issue imply, science now has a central and urgent part to play.

—ANDREW SUGDEN, CAROLINE ASH, BROOKS HANSON, JESSE SMITH
The Struggle to Govern the Commons

Thomas Dietz,¹ Elinor Ostrom,² Paul C. Stern³*

Human institutions—ways of organizing activities—affect the resilience of the environment. Locally evolved institutional arrangements governed by stable communities and buffered from outside forces have sustained resources successfully for centuries, although they often fail when rapid change occurs. Ideal conditions for governance are increasingly rare. Critical problems, such as transboundary pollution, tropical deforestation, and climate change, are at larger scales and involve nonlocal influences. Promising strategies for addressing these problems include dialogue among interested parties, officials, and scientists; complex, redundant, and layered institutions; a mix of institutional types; and designs that facilitate experimentation, learning, and change.

In 1968, Hardin (1) drew attention to two human factors that drive environmental change. The first factor is the increasing demand for natural resources and environmental services, stemming from growth in human population and per capita resource consumption. The second factor is the way in which humans organize themselves to extract resources from the environment and eject effluents into it—what social scientists refer to as institutional arrangements. Hardin’s work has been highly influential (2) but has long been aptly criticized as oversimplified (3–6).

Hardin’s oversimplification was twofold: He claimed that only two state-established institutional arrangements—centralized government and private property—could sustain commons over the long run, and he presumed that resource users were trapped in a commons dilemma, unable to create solutions (7–9). He missed the point that many social groups, including the herders on the commons that provided the metaphor for his analysis, have struggled successfully against threats of resource degradation by developing and maintaining self-governing institutions (3, 10–13). Although these institutions have not always succeeded, neither have Hardin’s preferred alternatives of private or state ownership.

In the absence of effective governance institutions at the appropriate scale, natural resources and the environment are in peril from increasing human population, consumption, and deployment of advanced technologies for resource use, all of which have reached unprecedented levels. For example, it is estimated that “the global ocean has lost more than 90% of large predatory fishes” with an 80% decline typically occurring “within 15 years of industrialized exploitation” (14). The threat of massive ecosystem degradation results from an interplay among ocean ecologies, fishing technologies, and inadequate governance.

Inshore fisheries are similarly degraded where they are open access or governed by top-down national regimes, leaving local and regional officials and users with insufficient autonomy and understanding to design effective institutions (15, 16). For example, the degraded inshore ground fishery in Maine is governed by top-down rules based on models that were not credible among users. As a result, compliance has been relatively low and there has been strong resistance to strengthening existing restrictions. This is in marked contrast to the Maine lobster fishery, which has been governed by formal and informal user institutions that have strongly influenced state-level rules that restrict fishing. The result has been credible rules with very high levels of compliance (17–19). A comparison of the landings of ground fish and lobster since 1980 is shown in Fig. 1. The rules and high levels of compliance related to lobster appear to have prevented the destruction of this fishery but probably are not responsible for the sharp rise in abundance and landings after 1986.

Resources at larger scales have also been successfully protected through appropriate international governance regimes such as the Montreal Protocol on stratospheric ozone and the International Commission for the Protection of the Rhine Agreements (20–24). Figure 2 compares the trajectory of atmospheric concentrations of ozone-depleting substances (ODS) with that of carbon dioxide since 1982. The Montreal Protocol, the centerpiece of the international agreements on ozone depletion, was signed in 1987. Before then, ODS concentrations were increasing faster than those of CO₂; the increases slowed by the early 1990s and the concentration appears to have stabilized in recent years. The international treaty regime to reduce the anthropogenic impact on stratospheric ozone is widely considered an example of a successful effort to protect the global commons. In contrast, international efforts to reduce greenhouse gas concentrations have not yet had an impact.

Knowledge from an emerging science of human-environment interactions, sometimes called human ecology or the “second environmental science” (25, 26), is clarifying the characteristics of institutions that facilitate or undermine sustainable use of environmental resources under particular conditions (6, 27). The knowledge base is strongest with small-scale ecologies and institutions, where long time series exist on many successes and failures. It is now developing for larger-scale systems. In this review, we address what science has learned about governing the commons and why it is always a struggle (28).

Why a Struggle?

Devising ways to sustain the earth’s ability to support diverse life, including a reasonable quality of life for humans, involves making tough decisions under uncertainty, complexity, and substantial biophysical constraints as well as conflicting human values and interests. Devising effective governance systems is akin to a coevolutionary race. A set of rules crafted to fit one set of socioecological conditions can erode as social, economic, and

Fig. 1. Comparison of landings of ground fish (gadoids, solid blue line) and lobster (dashed red line) in Maine from 1980 to 2002. Measured in millions of kilograms of ground fish and lobsters landed per year. International fishing in these waters ended with the extended jurisdiction that occurred in 1977 (155).
technological developments increase the potential for human damage to ecosystems and even to the biosphere itself. Furthermore, humans devise ways of evading governance rules. Thus, successful commons governance requires that rules evolve.

Effective commons governance is easier to achieve when (i) the resources and use of the resources by humans can be monitored, and the information can be verified and understood at relatively low cost (e.g., trees are easier to monitor than fish, and lakes are easier to monitor than rivers) (29); (ii) rates of change in resources, resource-user populations, technology, and economic and social conditions are moderate (30–32); (iii) communities maintain frequent face-to-face communication and dense social networks—sometimes called social capital—that increase the potential for trust, allow people to express and see emotional reactions to distrust, and lower the cost of monitoring behavior and inducing rule compliance (33–36); (iv) outsiders can be excluded at relatively low cost from using the resource (new entrants add to the harvesting pressure and typically lack understanding of the rules); and (v) users support effective monitoring and rule enforcement (37–39). Few settings in the world are characterized by all of these conditions. The challenge is to devise institutional arrangements that help to establish such conditions or, as we discuss below, meet the main challenges of governance in the absence of ideal conditions (6, 40, 41).

Selective Pressures

The characteristics of resources and social interaction in many subsistence societies present favorable conditions for the evolution of effective self-governing resource institutions (13). Hundreds of documented examples exist of long-term sustainable resource use in such communities as well as in more economically advanced communities with effective, local, self-governing rights, but there are also many failures (6, 11, 42–44). As human communities have expanded, the selective pressures on environmental governance institutions increasingly have come from broad influences. Commerce has become regional, national, and global, and institutions at all of these levels have been created to enable and regulate trade, transportation, competition, and conflict (45, 46). These institutions shape environmental impact, even if they are not designed with that intent. They also provide mechanisms for environmental governance (e.g., national laws) and part of the social context for local efforts at environmental governance. Larger scale governance may authorize local control, help it, hinder it, or override it (47–52). Now, every local place is strongly influenced by global dynamics (48, 53–57).

The most important contemporary environmental challenges involve systems that are intrinsically global (e.g., climate change) or are tightly linked to global pressures (e.g., timber production for the world market) and that require governance at levels from the global all the way down to the local (48, 58, 59). These situations often feature environmental outcomes spatially displaced from their causes and hard-to-monitor, larger scale economic incentives that may not be closely aligned with the condition of local ecosystems. Also, differentials in power within user groups or across scales allow some to ignore rules of commons use or to reshape the rules in their own interest, such as when global markets reshape demand for local resources (e.g., forests) in ways that swamp the ability of locally evolved institutions to regulate their use (60–62).

**Fig. 2.** Atmospheric concentration of CO$_2$ (solid blue line, right scale) and three principal ODS (dashed red line, left scale). The ODS are chlorofluorocarbons (CFCs) 11, 12, and 113 and are weighted based on their ozone-depleting potential (156). Data are from (157). ppt, parts per trillion; ppm, parts per million.

The store of governance tools and ways to modify and combine them is far greater than often is recognized (6, 63–65). Global and national environmental policy frequently ignores community-based governance and traditional tools, such as informal communication and sanctioning, but these tools can have significant impact (63, 66). Further, no single broad type of ownership—government, private, or community—uniformly succeeds or fails to halt major resource deterioration, as shown for forests in multiple countries (supporting online material text, figs. S1 to S5, and table S1).

Requirements of Adaptive Governance in Complex Systems

*Providing information.* Environmental governance depends on good, trustworthy information about stocks, flows, and processes within the resource systems being governed, as well as about the human-environment interactions affecting those systems. This information must be congruent in scale with environmental events and decisions (48, 67). Highly aggregated information may ignore or average out local information that is important in identifying future problems and developing solutions.

For example, in 2002, a moratorium on all fishing for northern cod was declared by the Canadian government after a collapse of this valuable fishery. An earlier near-collapse had led Canada to declare a 200-mile zone of exclusive fisheries jurisdiction in 1977 (68, 69). Considerable optimism existed during the 1980s that the stocks, as estimated by fishery scientists, were rebuilding. Consequently, generous total catch limits were established for northern cod and other ground fish, the number of licensed fishers was allowed to increase considerably, and substantial government subsidies were allocated for new vessels (70). What went wrong? There were a variety of information-related problems including: (i) treating all northern cod as a single stock instead of recognizing distinct populations with different characteristics, (ii) ignoring the variability of year classes of northern cod, (iii) focusing on offshore-fishery landing data rather than inshore data to “tune” the stock assessment, and (iv) ignoring inshore fishers who were catching ever-smaller fish and doubted the validity of stock assessments (70–72). This experience illustrates the need to collect and model both local and aggregated information about resource conditions and to use it in making policy at the appropriate scales.

Information also must be congruent with decision makers’ needs in terms of timing, content, and form of presentation (73–75). Informational systems that simultaneously meet high scientific standards and serve ongoing needs of decision makers and users are particularly useful. Information must not overload the capacity of users to assimilate it. Systems that adequately characterize environmental conditions or human activities with summary indicators such as prices for products or emission permits, or certification of good environmental performance can provide valuable signals as long as they are attentive to local as well as aggregate conditions (76–78).

Effective governance requires not only factual information about the state of the environment and human actions but also information about uncertainty and values. Scientific understanding of coupled human-biophysical systems will always be uncertain because of inherent unpredictability in the systems and because the science is never complete (79). Decision makers need information that characterizes the types and magnitudes of this uncertainty, as well as the nature and extent of scientific ignorance and disagreement (80). Also, because every environmental decision requires tradeoffs,
knowledge is needed about individual and social values and about the effects of decisions on various valued outcomes. For many environmental systems, local and easily captured values (e.g., the market value of lumber) have to be balanced against global, diffuse, and hard-to-capture values (e.g., biodiversity and the capability of humans and ecosystems to adapt to unexpected events). Finding ways to measure and monitor the outcomes for such varied values in the face of globalization is a major informational challenge for governance.

*Dealing with conflict.* Sharp differences in power and in values across interested parties make conflict inherent in environmental choices. Indeed, conflict resolution may be as important a motivation for designing resource institutions as it is concern with the resources themselves (81). People bring varying perspectives, interests, and fundamental philosophies to problems of environmental governance (74, 82–84), and their conflicts, if they do not escalate to the point of dysfunction, can spark learning and change (85, 86).

For example, a broadly participatory process was used to examine alternative strategies for regulating the Mississippi River and its tributaries (87). A dynamic model was constructed with continuous input by the Corps of Engineers, the Fish and Wildlife Service, local landowners, environmental groups, and academics from multiple disciplines. After extensive model development and testing against past historical data, most stakeholders had high confidence in the explanatory power of the model. Consensus was reached over alternative management options, and the resulting policies generated far less conflict than had existed at the outset (88).

Delegating authority to environmental ministries does not always resolve conflicts satisfactorily, so governments are experimenting with various governance approaches to complement managerial ones. They range from ballots and polls, where engagement is passive and participants interact minimally, to adversarial processes that allow parties to redress grievances through formal legal procedures, to various experiments with intense interaction and deliberation aimed at negotiating decisions or allowing parties in potential conflict to provide structured input to them through participatory processes (89–93).

*Inducing rule compliance.* Effective governance requires that the rules of resource use are generally followed, with reasonable standards for tolerating modest violations. It is generally most effective to impose modest sanctions on first offenders, and gradually increase the severity of sanctions for those who do not learn from their first or second encounter (39, 94). Community-based institutions often use informal strategies for achieving compliance that rely on participants’ commitment to rules and subtle social sanctions. Whether enforcement mechanisms are formal or informal, those who impose them must be seen as effective and legitimate by resource users or resistance and evasion will overwhelm the commons governance strategy.

Much environmental regulation in complex societies has been “command and control.” Governments require or prohibit specific actions or technologies, with fines or jail terms possible for punishing rule breakers. If sufficient resources are made available for monitoring and enforcement, such approaches are effective. But when governments lack the will or resources to protect “protected areas” (95–97), when major environmental damage comes from hard-to-detect “nonpoint sources,” and when the need is to encourage innovation in behaviors or technologies rather than to require or prohibit familiar ones, command and control approaches are less effective. They are also economically inefficient in many circumstances (98–100).

Financial instruments can provide incentives to achieve compliance with environmental rules. In recent years, market-based systems of tradable environmental allowances (TEAs) that define a limit to environmental withdrawals or emissions and permit free trade of allocated allowances under those limits have become popular (76, 101, 102). TEAs are one of the bases for the Kyoto agreement on climate change.

Economic theory and experience in some settings suggest that these mechanisms have substantial advantages over command and control (103–106). TEAs have exhibited good environmental performance and economic efficiency in the U.S. Sulfur Dioxide Allowance Market intended to reduce the prevalence of acid rain (107, 108) and the Lead Phasedown Program aimed at reducing the level of lead emissions (109). Crucial variables that differentiate these highly successful programs from less successful ones, such as chlorofluorocarbon production quota trading and the early EPA emission trading programs, include: (i) the level of predictability of the stocks and flows, (ii) the number of users or producers who are regulated, (iii) the heterogeneity of the regulated users, and (iv) clearly defined and fully exchangeable permits (110).

TEAs, like all institutional arrangements, have notable limitations. TEA regimes tend to leave unprotected those resources not specifically covered by trading rules (e.g., by-catch of noncovered fish species) (111) and to suffer when monitoring is difficult (e.g., under the Kyoto protocol, the question of whether geologically sequestered carbon will remain sequestered). Problems can also occur with the initial allocation of allowances, especially when historic users, who may be called on to change their behavior most, have disproportionate power over allocation decisions (76, 101). TEAs and community-based systems appear to have opposite strengths and weaknesses (101), suggesting that institutions that combine aspects of both systems may work better than either approach alone. For example, the fisheries tradable permit system in New Zealand has added management institutions to complement the market institutions (102, 112).

Voluntary approaches and those based on information disclosure have only begun to receive careful scientific attention as supplements to other tools (63, 77, 113–115). Success appears to depend on the existence of incentives that benefit leaders in volunteering over laggards and on the simultaneous use of other strategies, particularly ones that create incentives for compliance (77, 116–118). Difficulties of sanctioning pose major problems for international agreements (119–121).

*Providing infrastructure.* The importance of physical and technological infrastructure is often ignored. Infrastructure, including technology, determines the degree to which a commons can be exploited (e.g., water works and fishing technology), the extent to which waste can be reduced in resource use, and the degree to which resource conditions and the behavior of humans users can be effectively monitored. Indeed, the ability to choose institutional arrangements depends in part on infrastructure. In the absence of barbed-wire fences, for example, enforcing private property rights on grazing lands is expensive, but with barbed wire fences, it is relatively cheap (122). Effective communication and transportation technologies are also of immense importance. Fishers who observe an unauthorized boat or harvesting technology can use a radio or cellular phone to alert others to illegal actions (123). Infrastructure also affects the links between local commons and regional and global systems. Good roads can provide food in bad times but can also open local resources to global markets, creating demand for resources that cannot be used locally (124). Institutional infrastructure is also important, including research, social capital, and multilevel rules, to coordinate between local and larger levels of governance (48, 125, 126).

Be prepared for change. Institutions must be designed to allow for adaptation because some current understanding is likely to be wrong, the required scale of organization can shift, and biophysical and social systems can change. Fixed rules are likely to fail because they place too much confidence in the current state of knowledge, whereas systems that guard against the low probability, high consequence possibilities and allow for change may be suboptimal in the short run but prove wiser in the long run. This is a principal lesson of adaptive management research (31, 127).

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Strategies for Meeting the Requirements of Adaptive Governance

The general principles for robust governance institutions for localized resources (Fig. 3) are well established as a result of multiple empirical studies (13, 39, 128-137). Many of these also appear to be applicable to regional and global resources (138), although they are less well tested at those scales. Three of them seem to be particularly relevant for problems at larger scales.

Analytic deliberation. Well-structured dialogue involving scientists, resource users, and interested publics, and informed by analysis of key information about environmental and human-environment systems, appears critical. Such analytic deliberation (74, 139, 140) provides improved information and the trust in it that is essential for information to be used effectively, builds social capital, and can allow for change and deal with inevitable conflicts well enough to produce consensus on governance rules. The negotiated 1994 U.S. regulation on disinfectant by-products in water that reached an interim consensus, including a decision to collect new information and reconsider the rule on that basis (74), is an excellent example of this approach.

Nesting. Institutional arrangements must be complex, redundant, and nested in many layers (32, 141, 142). Simple strategies for governing the world’s resources that rely exclusively on imposed markets or one-level, centralized command and control and that eliminate apparent redundancies in the name of efficiency have been tried and have failed. Catastrophic failures often have resulted when central governments have exerted sole authority over resources. Examples include the massive environmental degradation and impoverishment of local people in Indonesian Borneo (95), the increased rate of loss and fragmentation of high-quality habitat that occurred after creating the Wolong Nature Reserve in China (143), and the closing of the northern cod fishery along the eastern coast of Canada partly attributable to the excessive quotas granted by the Canadian government (70).

Institutional variety. Governance should employ mixtures of institutional types (e.g., hierarchies, markets, and community self-governance) that employ a variety of decision rules to change incentives, increase information, monitor use, and induce compliance (6, 63, 117). Innovative rule evaders can have more trouble with a multiplicity of rules than with a single type of rule.

Conclusion

Is it possible to govern such critical commons as the oceans and the climate? We remain guardedly optimistic. Thirty-five years ago it seemed that the “tragedy of the commons” was inevitable everywhere not owned privately or by a government. Systematic multidisciplinary research has, however, shown that a wide diversity of adaptive governance systems have been effective stewards of many resources. Sustained research coupled to an explicit view of national and international policies as experiments can yield the scientific knowledge necessary to design appropriate adaptive institutions.

Sound science is necessary for commons governance, but not sufficient. Too many strategies for governance of local commons are designed in capital cities or by donor agencies in ignorance of the state of the science and local conditions. The results are often tragic, but at least these tragedies are local. As the human footprint on the Earth enlarges (144), humanity is challenged to develop and deploy understanding of large-scale commons governance quickly enough to avoid the large-scale tragedies that will otherwise ensue.

References and Notes
2. See [6, 145]. It was the paper most frequently cited as having the greatest career impact in a recent survey of biologists (146). A search performed by L. Wisen on 22 and 23 October 2003 on the Workshop Library Common-Pool Resources database (147) revealed that, before Hardin’s paper, only 19 articles had been written in English-language academic literature with a specific reference to “commons,” “common-pool resources,” or “common property” in the title. Since then, attention to the commons has grown rapidly. Since 1968, a total of over 2300 articles in that database contain a specific reference to one of these three terms in the title.
17. J. Acheson, Capturing the Commons: Devising Institutions to Manage the Maine Lobster Industry (Univ. Press of New England, Hanover, NH, 2003).
19. J. Wilson, personal communication.

Fig. 3. General principles for robust governance of environmental resources (green, left and right columns) and the governance requirements they help meet (yellow, center column) (13, 158). Each principle is relevant for meeting several requirements. Arrows indicate some of the most likely connections between principles and requirements. Principles in the right column may be particularly relevant for global and regional problems.
**Social Capital and the Collective Management of Resources**

**Jules Pretty**

The proposition that natural resources need protection from the destructive actions of people is widely accepted. Yet communities have shown in the past and increasingly today that they can collaborate for long-term resource management. The term social capital captures the idea that social bonds and norms are critical for sustainability. Where social capital is high in formalized groups, people have the confidence to invest in collective activities, knowing that others will do so too. Some 0.4 to 0.5 million groups have been established since the early 1990s for watershed, forest, irrigation, pest, wildlife, fishery, and microfinance management. These offer a route to sustainable management and governance of common resources.

From Malthus to Hardin and beyond, analysts and policy-makers have widely come to accept that natural resources need to be protected from the destructive, yet apparently rational, actions of people. The compelling logic is that people inevitably harm natural resources as they use them, and more people therefore do more harm. The likelihood of this damage being greater where natural resources are commonly owned is further increased by suspicions that people tend to free-ride, both by overusing and underinvesting in the maintenance of resources. As our global numbers have increased, so the evidence of harm to water, land, and atmospheric resources has emerged, so the choices seem to be starker. Either we regulate to prevent further harm, in Hardin’s words (/), to engage in mutual coercion mutually agreed upon, or we press ahead with enclosure and privatization to increase the likelihood that resources will be more carefully managed.

These concepts have influenced many policy-makers and practitioners. They have
led, for example, to the popular wilderness myth (2)—that many ecosystems are pristine and have emerged independent of the actions of local people, whether positive or negative. Empty, idle, and “natural” environments need protection from harmful large-scale developers, loggers, and ranchers, as well as from farmers, hunters, and gatherers (3). Since the first national park was set up at Yellowstone in 1872, some 12,750 protected areas of greater than 1000 hectares have been established worldwide. Of the 7322 protected areas in developing countries where many people rely on wild resources for food, fuel, medicine, and feed, 30% covering 6 million km² are strictly protected, permitting no use of resources (4).

The removal of people, often the poorest and the indigenous (3), from the very resources on which they most rely has a long and troubling history and has framed much natural resource policy in both developing and industrialized countries (6). Yet common property resources remain immensely valuable for many people, and exclusion can be costly for them. In India, for example, common resources have been estimated to contribute some US$5 billion year⁻¹ to the income of the rural poor (7).

An important question is could local people play a positive role in conservation and management of resources? And if so, how best can unfettered private actions be mediated in favor of the common good? Though some communities have long been known to manage common resources such as forests and grazing lands effectively over long periods without external help (8), recent years have seen the emergence of local groups as an effective option instead of strict regulation or enclosure. This “third way” has been shaped by theoretical developments in the governance of the commons and in thinking on social capital (9, 10). These groups are indicating that, given good knowledge about local resources; appropriate institutional, social, and economic conditions (11); and processes that encourage careful deliberation (12), communities can work together collectively to use natural resources sustainably over the long term (13).

### Social Capital and Local Resource Management Groups

The term social capital captures the idea that social bonds and norms are important for people and communities (14). It emerged as a term after detailed analyses of the effects of social cohesion on regional incomes, civil society, and life expectancy (15–17). As social capital lowers the transaction costs of working together, it facilitates cooperation. People have the confidence to invest in collective activities, knowing that others will also do so. They are also less likely to engage in unfettered private actions with negative outcomes, such as resource degradation (18, 19). Four features are important: relations of trust; reciprocity and exchanges; common rules, norms, and sanctions; and connectedness in networks and groups.

Relations of trust lubricate cooperation, and so reduce transaction costs between people. Instead of having to invest in monitoring others, individuals are able to trust them to act as expected, thus saving money and time. But trust takes time to build and is easily broken. When a society is pervaded by distrust or conflict, cooperative arrangements are unlikely to emerge (20). Reciprocity increases trust, and refers to simultaneous exchanges of goods and knowledge of roughly equal value, or continuing relations over time (14, 15). Reciprocity contributes to the development of long-term obligations between people, which helps in achieving positive environmental outcomes.

Common rules, norms, and sanctions are the mutually agreed upon or handed-down drivers of behavior that ensure group interests are complementary with those of individuals. These are sometimes called the rules of the game (21), and they give individuals the confidence to invest in the collective good. Sanctions ensure that those who break the rules know they will be punished. Three types of connectedness (bonding, bridging, and linking) have been identified as important for the networks within, between, and beyond communities (22). Bonding social capital describes the links between people with similar objectives and is manifested in local groups, such as guilds, mutual-aid societies, sports clubs, and mothers’ groups. Bridging describes the capacity of such groups to make links with others that may have different views, and linking describes the ability of groups to engage with external agencies, either to influence their policies or to draw on useful resources.

But do these ideas work in practice? First, there is evidence that high social capital is associated with improved economic and social well being. Households with greater connectedness tend to have

### Table 1. Social capital formation in selected agricultural and rural resource management sectors (since the early 1990s). This table suggests that 455,000 to 520,000 groups have been formed. Additional groups have been formed in farmers’ research, fishery, and wildlife programs in a wide variety of countries (21).

<table>
<thead>
<tr>
<th>Countries and programs</th>
<th>Watershed and catchment groups</th>
<th>Local groups (thousand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia (4500 Landcare groups containing about one-third of all farmers), Brazil (15,000 to 17,000 microbacias groups), Guatemala, and Honduras (700 to 1100 groups), India (30,000 groups in both state government and nongovernmental organization programs), Kenya (3000 to 4500 Ministry of Agriculture catchment committees), United States (1000 farmer-led watershed initiatives)</td>
<td>54 to 58</td>
<td></td>
</tr>
<tr>
<td>Irrigation water users’ groups</td>
<td>Sri Lanka, Nepal, India, Philippines, and Pakistan (water users groups as part of government irrigation programs)</td>
<td>58</td>
</tr>
<tr>
<td>Microfinance institutions</td>
<td>Bangladesh (Grameen Bank and Proshika), Nepal, India, Sri Lanka, Vietnam, China, Philippines, Fiji, Tonga, Solomon Islands, Papua New Guinea, Indonesia, and Malaysia</td>
<td>252 to 295</td>
</tr>
<tr>
<td>Joint and participatory forest management</td>
<td>India and Nepal (joint forest management and forest protection committees)</td>
<td>73</td>
</tr>
<tr>
<td>Integrated pest management</td>
<td>Indonesia, Vietnam, Bangladesh, Sri Lanka, China, Philippines, and India (farmers trained in farmer field schools)</td>
<td>18 to 36</td>
</tr>
</tbody>
</table>
higher incomes, better health, higher educational achievements, and more constructive links with government (4, 9, 15, 16, 23). What, then, can be done to develop appropriate forms of social organization that structurally suit natural resource management?

Collective resource management programs that seek to build trust, develop new norms, and help form groups have become increasingly common, and such programs are variously described by the terms community-, participatory-, joint-, decentralized-, and co-management. They have been effective in several sectors, including watershed, forest, irrigation, pest, wildlife, fishery, farmers’ research, and micro-finance management (Table 1). Since the early 1990s, some 400,000 to 500,000 new local groups were established in varying environmental and social contexts (18), mostly evolving to be of similar small size, typically with 20 to 30 active members, putting total involvement at some 8 to 15 million households. The majority continue to be successful and show the inclusive characteristics identified as vital for improving community well-being (24), and evaluations have confirmed that there are positive ecological and economic outcomes, including for water-sheds (23), forests (25), and pest management (26, 27).

Further Challenges

The formation, persistence, and effects of new groups suggests that new configurations of social and human relations could be prerequisites for long-term improvements in natural resources. Regulations and economic incentives play an important role in encouraging changes in behavior, but although these may change practices, there is no guaranteed positive effect on personal attitudes (28). Without changes in social norms, people often revert to old ways when incentives end or regulations are no longer enforced, and so long-term protection may be compromised.

However, there remains a danger of appearing too optimistic about local groups and their capacity to deliver economic and environmental benefits, because divisions within and between communities can result in environmental damage. Moreover, not all forms of social relations are necessarily good for everyone. A society may have strong institutions and embedded reciprocal mechanisms yet be based on fear and power, such as feudal and unjust societies. For example, rules and norms can also trap people within harmful social arrangements, and the role of men may be enhanced at the expense of women. Some associations may act as obstacles to the emergence of sustainability, encouraging conformity, perpetuating inequity, and allowing certain individuals to shape their institutions to suit only themselves; in this sense, social capital can also have its “dark side” (29).

Social capital can help to ensure compliance with rules and keep down monitoring costs, provided networks are dense, with frequent communication and reciprocal arrangements, small group size, and lack of easy exit options for members. However, factors relating to the natural resources themselves, particularly whether they are stationary, have high storage capacity (potential for biological growth), and clear boundaries, will also play a critical role in affecting whether social groups can succeed, keep down the costs of enforcement, and ensure positive resource outcomes (30).

Communities also do not always have the knowledge to appreciate that what they are doing may be harmful. For instance, it is common for fishing communities to believe that fish stocks are not being eroded, even though the scientific evidence indicates otherwise. Local groups may need the support of higher level authorities, for example with legal structures that give communities clear entitlement to land and other resources as well as insulation from the pressures of global markets (8, 9). For global environmental problems, such as climate change, governments may need to regulate, partly because no community feels it can have a perceptible impact on a global problem. Thus, effective international institutions are needed to complement local ones (31).

Nonetheless, the ideas of social capital and governance of the commons, combined with the recent successes of local groups, offer routes for constructive and sustainable outcomes for natural resources in many of the world’s ecosystems. To date, however, the triumphs of the commons have been largely at local to regional level, where resources can be closed-access and where institutional conditions and market pressures are supportive. The greater challenge will center on applying some of these principles to open-access commons and worldwide environmental threats and creating the conditions by which social capital can work under growing economic globalization.

References and Notes

11. T. O’Riordan, S. Stoll-Kleemann, Biodiversity, Sustainability and Human Communities (Earthscan, London, 2002).
27. See the following websites for more data and evaluations on the ecological and economic impact of local groups: (i) Sustainable agriculture projects—analysis of 208 projects in developing countries in which social capital formation was critical prerequisite of success, see http://www2.essex.ac.uk/ces/researchProgrammes/ subhead/s4foodprodinc.htm. Also see (32), (ii) Joint forest management (JFM) projects in India. For impacts in Andhra Pradesh, including satellite photographs, see www.apnic.in/oapers/jfm.htm. For case studies of JFM, see www.terin.org/jfm/cs.htm and www.ijfm.org/databank/jfm/jfm.html. See also (25, 33), (iii) For community IPM, see www.communitygym.org/ and (26), (iv) For impacts on economic success in rural communities, see (34, 35), (v) For Landcare program in Australia, where 4500 groups have formed since 1989, see www. landcareaustralia.com.au/projectlist.asp and www.landcareaustralia.com.au/learningCenterOutbrief.p hp.
36. I am grateful for helpful comments on an earlier version of this paper by H. Ward and J. Morison, together with those of two anonymous referees.

Web Resources

www.sciencemag.org/cgi/content/full/302/5652/1912/DC1
Managing Tragedies: Understanding Conflict over Common Pool Resources

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Conflicts over the management of common pool resources are not simply material. They also depend on the perceptions of the protagonists. Policy to improve management often assumes that problems are self-evident, but in fact careful and transparent consideration of the ways different stakeholders understand management problems is essential to effective dialogue.

The management of common pool resources can be viewed as a problem of collective action and analyzed in terms of the costs and benefits of cooperation, institutional development, and monitoring, according to variables such as group size, composition, relationship with external powers, and resource characteristics (1–5). However, resulting policy debates are often flawed because of the assumption that the actors involved share an understanding of the problem that is being discussed. They tend to ignore the fact that the assumptions, knowledge, and understandings that underlie the definition of resource problems are frequently uncertain and contested.

Recent policy debates over natural resource management have revealed the unexpected consequences of the assumption that problems (and therefore solutions) are self-evident. For example, in the 1970s and 1980s, governments and donors in Asia and sub-Saharan Africa perceived an impending fuel wood crisis. In response, they developed social forestry projects to persuade smallholders to plant trees on their farmlands, assuming that the aggregate assessment of shortages reflected an acute need for fuel wood at the household level. Subsequent research showed that the assumptions behind these interventions were deeply flawed (6, 7). Some households indeed planted trees to provide fuel. Many others responded to scarcity by sharing cooking arrangements, increasing labor devoted to collection, substituting between fuels, migrating, or engaging in nomadism and transhumance. Furthermore, those farmers who planted trees primarily did so as a cash crop to be sold for pulp, small timber, and poles, not as a subsistence commodity for fuel wood. The problem of fuel wood scarcity, as perceived by government planners and donors, was quite different from the problems of primary concern to small farmers, who were trying to secure access to sustainable livelihood options by optimizing the use of their land and labor resources.

Similarly, concern over appropriate rangeland use in Africa has long been dominated by the perception that pastures were being overstocked (8). A variety of self-evident notions supported this, including the idea that cattle were kept purely for prestige and that use of commonly held pastures could not be regulated. Subsequent research into dry-land ecology, herd use, and pasture management suggest that high stocking rates can make sense where ecosystem productivity is driven by variable rainfall (9–11). Too many livestock will still cause problems for some herders, but there are no grounds for the unmitigated gloom surrounding policy debates about the overstocking of these rangelands.

Defining Resource Management Problems

Problem definition is critical to the process of making policy, yet its role is rarely scrutinized. Stakeholders often do not explicitly recognize the ways in which their knowledge and understanding frame their perspectives on common pool resource management policy. Although conflict is a feature of many resource management regimes, it is often assumed to reflect differences in material interests between stakeholders. In such circumstances, conflict may be managed by trading off different management objectives (12) or by attempting to reconcile multiple interests in resource management (13).

We suggest that the origins of conflict go beyond material incompatibilities. They arise at a deeper cognitive level. In our view, stakeholders draw on their current knowledge and understanding to cognitively frame a specific common pool resource management problem. Thus, differences in knowledge, understanding, preconceptions, and priorities are often obscured in conventional policy dialogue and may provide a deeper explanation of conflict. It is precisely when different stakeholders (of different sizes and operating at different levels) reveal different interpretations of key issues that the policy debate can be most productive. The knowledge which allows stakeholders to define the problems of resource use falls into three realms: knowledge of the empirical context; knowledge of laws and institutions; and beliefs, myths, and ideas.

Stakeholders’ knowledge of the empirical context derives from a variety of sources. At the local level, knowledge may derive from direct personal experience, particularly of extreme events such as droughts or floods. At larger scales, knowledge may reflect inference from known changes elsewhere, such as the insights of formal empirical and theoretical research by official agencies and research organizations using remote sensing, censuses, or sample surveys. Decision-makers and stakeholders are likely to differ in their access to, and understanding of, these diverse sources of knowledge. Thus, the knowledge of any particular stakeholder will be partial and hence may be contested by other actors.

The ideas, ideologies, and beliefs brought to bear on problem definition by different stakeholders can substantially influence problem perception. Religious beliefs and moral conviction can be important in structuring understanding, both among local people and scientists. Ideas derive legitimacy from received wisdom about theory [e.g., the widespread belief in the “Tragedy of the Commons” (14)] and from ideas outside formal science, including informal or “folk” knowledge. Policy narratives or story lines can exert a powerful influence on official decision-makers’ perceptions of resource management problems (15–17). Divergent received wisdoms used by different actors in their analysis are a potent source of conflict over appropriate response options. Most common pool resource management situations do not operate in isolation.
from a wider context of the legal and institutional framework. Stakeholders differ in their knowledge of this framework: A local herder may be unaware of a country’s policy commitments under the Convention on Biological Diversity, whereas a state resource manager may be forced to act in particular ways because of commitments under such multilateral agreements. In this sense, knowledge about laws and institutions may be seen as providing both constraints and opportunities for common pool resource management, because this knowledge forces stakeholders to consider resource uses that are compatible with these wider policy processes. Importantly, knowledge about policy is likely to contribute to the way in which a stakeholder perceives a problem and hence the alternative responses that he or she is willing to consider.

Cognitive Conflict in Common Pool Resource Management

If each stakeholder is only able to define problems and test the set of possible response options in the context of his or her particular knowledge and understanding, then agreement is less likely, both in terms of perceptions and problem definition as well as over the desired response to the problem. Thus, policy conflict arises because differences in knowledge and understanding between stakeholders frame their perceptions of resource use problems as well as possible solutions to these problems (Fig. 1).

One cannot, therefore, simply analyze the economic interests of different claimants to rights over a defined resource. Different people will see different resources in a landscape. They will perceive different procedures appropriate for reconciling conflict. Moreover, perceptions will change, because different elements within the landscape will become “resources.” For example, a market may develop for something previously regarded locally as useless or destructive of value, such as wildlife tourism. In these situations, the realm of conflict between beneficiaries and others will be both cognitive and material.

Where cognitive conflict is important, policy dialogue needs to be structured so that differences in knowledge, understanding, ideas, and beliefs in the public arena are recognized. Ostrom’s seminal studies of the evolution of institutions of water management in California demonstrate the value of precisely this dialogue, and the absence of dialogue explains the failure of these institutions to emerge (18).

Similarly, Wilson has argued that only by making explicit the uncertainties and ignorance inherent in understanding of fisheries will it be possible to establish the collective learning experience necessary to manage resource use in such complex ecosystems (14).

Making explicit the basis of different stakeholders’ positions is likely to improve the transparency and effectiveness of negotiations between stakeholders by enabling actors to understand the plurality of views that prevail in the context of resource use and management. Failure to recognize the cognitive dimension of conflict results in superficial policy measures that fail to address the deeper underlying (structural) differences between resource users.

Of course, a deeper understanding of stakeholder differences over common pool resources does not guarantee that policy negotiations will result in win-win scenarios, but it may smooth the path toward consensus in situations where there are incompatibilities in stakeholders’ interests, values, or priorities. Management effectiveness will always be limited by incomplete knowledge and understanding of complex natural and social systems. Our type of reasoning will not help if decisions are driven by the unilateral political will or the economic power of particular stakeholders. If policy is made in a way that precludes dialogue, our approach will be of limited use, except to explain why things go wrong. This perspective on resource conflict can reveal the incompatibility of competing perceptions, but it cannot by itself reconcile them. Techniques for conflict resolution, negotiation, and management must then come into play. To some extent, policy will always involve “tragic” choices that contradict the deeply held values and beliefs of some stakeholders (19).

References and Notes

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Web Resources

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Fig. 1. Cognitive conflict over common pool resources.
Global Food Security: Challenges and Policies

Mark W. Rosegrant* and Sarah A. Cline

Global food security will remain a worldwide concern for the next 50 years and beyond. Recently, crop yield has fallen in many areas because of declining investments in research and infrastructure, as well as increasing water scarcity. Climate change and HIV/AIDS are also crucial factors affecting food security in many regions. Although agroecological approaches offer some promise for improving yields, food security in developing countries could be substantially improved by increased investment and policy reforms.

The ability of agriculture to support growing populations has been a concern for generations and continues to be high on the global policy agenda. The eradication of poverty and hunger was included as one of the United Nations Millennium Development Goals adopted in 2000. One of the targets of the Goals is to halve the proportion of people who suffer from hunger between 1990 and 2015 (1). Meeting this food security goal will be a major challenge. Predictions of food security outcomes have been a part of the policy landscape since Malthus’ An Essay on the Principle of Population of 1798 (2). Over the past several decades, some experts have expressed concern about the ability of agricultural production to keep up with global food demands (3–5), whereas others have forecast that technological advances or expansions of cultivated area would boost production sufficiently to meet rising demands (6–8). So far, dire predictions of a global food security catastrophe have been unfounded.

Nevertheless, crop yield growth has slowed in much of the world because of declining investments in agricultural research, irrigation, and rural infrastructure and increasing water scarcity. New challenges to food security are posed by climate change and the morbidity and mortality of human immunodeficiency virus/acquired immunodeficiency syndrome (HIV/AIDS). Many studies predict that world food supply will not be adversely affected by moderate climate change, by assuming farmers will take adequate steps to adjust to climate change and that additional CO₂ will increase yields (9). However, many developing countries are likely to fare badly. In warmer or tropical environments, climate change may result in more intense rainfall events between prolonged dry periods, as well as reduced or more variable water resources for irrigation. Such conditions may promote pests and disease on crops and livestock, as well as soil erosion and desertification. Increasing development of marginal lands may in turn put these areas at greater risk of environmental degradation (10, 11). The HIV/AIDS epidemic is another global concern, with an estimated 42 million cases worldwide at the end of 2002 (12); 95% of those are in developing countries. In addition to its direct health, economic, and social impacts, the disease also affects food security and nutrition. Adult labor is often removed from affected households, and these households will have less capacity to produce or buy food, as assets are often depleted for medical or funeral costs (13). The agricultural knowledge base will deteriorate as individuals with farming and science experience succumb to the disease (14). Can food security goals be met in the face of these old and new challenges?

Several organizations have developed quantitative models that project global food supply and demand into the future (15–19). According to the most recent baseline projections of the International Food Policy Research Institute’s (IFPRI’s) International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (20), global cereal production is estimated to increase by 56% between 1997 and 2050, and livestock production by 90%. Developing countries will account for 93% of cereal demand growth and 85% of meat-demand growth to 2050. Income growth and rapid urbanization are major forces driving increased demand for higher valued commodities, such as meats, fruits, and vegetables. International agricultural trade will increase substantially, with developing countries’ cereal imports doubling by 2025 and tripling by 2050. Child malnutrition will persist in many developing countries, although overall, the share of malnourished children is projected to decline from 31% in 1997 to 14% in 2050 (Fig. 1). Nevertheless, this represents a nearly 35-year delay in meeting the Millennium Development Goals. In some places, circumstances will deteriorate, and in sub-Saharan Africa, the number of malnourished preschool children will increase between 1997 and 2015, after which they will only decrease slightly until 2050. South Asia is another region of concern—although progress is expected in this region, more than 30% of preschool children will remain malnourished by 2030, and 24% by 2050 (21).

Achieving food security needs policy and investment reforms on multiple fronts, including human resources, agricultural research, rural infrastructure, water resources, and farm- and community-based agricultural and natural resources management. Progressive policy action must not only increase agricultural production, but also boost incomes and reduce poverty in rural areas where most of the poor live. If we take such an approach, we can expect production between 1997 and 2050 to increase by 71% for cereals and by 131% for meats. A reduction in childhood malnutrition would follow; the number of malnourished children would decline from 33 million in 1997 to 16 million in 2050 in sub-Saharan Africa, and from 85 million to 19 million in South Asia (Fig. 1).

Increased investment in people is essential to accelerate food security improvements. In agricultural areas, education works directly to enhance the ability of farmers to adopt more...
advanced technologies and crop-management techniques and to achieve higher rates of return on land (22). Moreover, education encourages movement into more remunerative nonfarm work, thus increasing household income. Women’s education affects nearly every dimension of development, from lowering fertility rates to raising productivity and improving environmental management (23). Research in Brazil shows that 25% of children were stunted if their mothers had four or fewer years of schooling; however, this figure fell to 15% if the mothers had a primary education and to 3% if mothers had any secondary education (24). Poverty reduction is usually enhanced by an increase in the proportion of educational resources going to primary education and to the poorest groups or regions (25–27). Investments in health and nutrition, including safe drinking water, improved sewage disposal, immunization, and public health services, also contribute to poverty reduction. For example, a study in Ethiopia shows that the distance to a water source, as well as nutrition and morbidity, all affect agricultural productivity of households (28).

When rural infrastructure has deteriorated or is nonexistent, the cost of marketing farm produce, and thus escaping subsistence agriculture and improving incomes, can be prohibitive for poor farmers. Rural roads increase agricultural production by bringing new land into cultivation and by intensifying existing land use, as well as consolidating the links between agricultural and nonagricultural activities within rural areas and between rural and urban areas (29). Government expenditure on roads is the most important factor in poverty alleviation in rural areas of India and China, because it leads to new employment opportunities, higher wages, and increased productivity (30, 31).

In addition to being a primary source of crop and livestock improvement, investment in agricultural research has high economic rates of return (32). Three major yield-enhancing strategies include research to increase the harvest index (33), plant biomass, and stress tolerance (particularly drought resistance) (34, 35). For example, the hybrid “New Rice for Africa,” which was bred to grow in the uplands of West Africa, produces more than 50% more grain than current varieties when cultivated in traditional rainfed systems without fertilizers. Moreover, this variety matures 30 to 50 days earlier than current varieties and has enhanced disease and drought tolerance (36). In addition to conventional breeding, recent developments in nonconventional breeding, such as marker-assisted selection and cell and tissue culture techniques, could be employed for crops in developing countries, even if these countries stop short of transgenic breeding. To date, however, application of molecular biotechnology has been mostly limited to a small number of traits of interest to commercial farmers, mainly developed by a few global life science companies.

Although much of the science and many of the tools and intermediate products of biotechnology are transferable to solve high-priority problems in the tropics and subtropics, it is generally agreed that the private sector will not invest sufficiently to make the needed adaptations in these regions with limited market potential. Consequently, the public sector will have to play a key role, much of it by accessing proprietary tools and products from the private sector (37).

Irrigation is the largest water user worldwide, but also the first sector to lose out as scarcity increases (38). The challenges of water scarcity are heightened by the increasing costs of developing new water sources, soil degradation in irrigated areas, groundwater depletion, water pollution, and ecosystem degradation. Wasteful use of already developed water supplies may be encouraged by subsidies and distorted incentives that influence water use. Hence, investment is needed to develop new water management policies and infrastructure. Although the economic and environmental costs of irrigation make many investments unprofitable, much could be achieved by water conservation and increased efficiency in existing systems and by increased crop productivity per unit of water used. Regardless, more research and policy efforts need to be focused on rainfed agriculture. Exploiting the full potential of rainfed agriculture will require investment in water harvesting technologies, crop breeding, and extension services, as well as good access to markets, credit, and supplies. Water harvesting and conservation techniques are particularly promising for the semi-arid tropics of Asia and Africa, where agricultural growth has been less than 1% in recent years. For example, water harvesting trials in Burkina Faso, Kenya, Niger, Sudan, and Tanzania show increases in yield of a factor of 2 to 3, compared with dryland farming systems (39, 40).

Agroecological approaches that seek to manage landscapes for both agricultural production and ecosystem services are another way of improving agricultural productivity. A study of 45 projects, using agroecological approaches, in 17 African countries shows cereal yield improvements of 50 to 100 percent (41). There are many concomitant benefits to such approaches, as they reduce pollution through alternative methods of nutrient and pest management, create biodiversity reserves, and enhance habitat quality through careful management of soil, water, and natural vegetation. Important issues remain about how to scale up agroecological approaches. Pilot programs are needed to work out how to mobilize private investment and to develop systems for payment of ecosystem services. All of these issues require investment in research, system development, and knowledge sharing.

To implement agricultural innovation, we need collective action at the local level, as well as the participation of government and nongovernmental organizations that work at the community level. There have been several successful programs, including those that use water harvesting and conservation techniques (42, 43). Another priority is participatory plant breeding for yield increases in rainfed agrosystems, particularly in dry and remote areas. Farmer participation can be used in the very early stages of breed selection to help find crops suited to a multitude of environments and farmer preferences. It may be the only feasible route for crop breeding in remote areas, where a high level of crop diversity is required within the same farm, or for minor crops that are neglected by formal breeding programs (44, 45).

Making substantial progress in improving food security will be difficult, and it does mean reform of currently accepted agricultural practices. However, innovations in agroecological approaches and crop breeding have brought some documented successes. Together with investment in research and water and transport infrastructure, we can make major improvements to global food security, especially for the rural poor.

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New Visions for Addressing Sustainability

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Attaining sustainability will require concerted interactive efforts among disciplines, many of which have not yet recognized, and internalized, the relevance of environmental issues to their main intellectual discourse. The inability of key scientific disciplines to engage interactively is an obstacle to the actual attainment of sustainability. For example, in the list of Millennium Development Goals from the United Nations World Summit on Sustainable Development, Johannesburg, 2002, the seventh of the eight goals, to “ensure environmental sustainability,” is presented separately from the parallel goals of reducing fertility and poverty, improving gains in equity, improving material conditions, and enhancing population health. A more integrated and consilient approach to sustainability is urgently needed.

For human populations, sustainability means transforming our ways of living to maximize the chances that environmental and social conditions will indefinitely support human security, wellbeing, and health. In particular, the flow of non-substitutable goods and services from ecosystems must be sustained. The contemporary stimulus for exploring sustainability is the accruing evidence that humankind is jeopardizing its own longer term interests by living beyond Earth’s means, thereby changing atmospheric composition and depleting biodiversity, soil fertility, ocean fisheries, and freshwater supplies (1).

Much early discussion about sustainability has focused on readily measurable intermediate outcomes such as increased economic performance, greater energy efficiency, better urban design, improved transport systems, better conservation of recreational amenities, and so on. However, such changes in technologies, behaviors, amenities, and equity are only the means to attaining desired human experiential outcomes, including autonomy, opportunity, security, and health. These are the true ends of sustainability—and there has been some recognition that their attainment, and their sharing, will be optimized by reducing the rich-poor divide (2).

Some reasons for the failure to achieve a collective vision of how to attain sustainability lie in the limitations of, and disjunction between, disciplines we think should be central to our understanding of sustainability: demography, economics, ecology, and epidemiology. These disciplines bear on the size and economic activities of the human population, how the population relates to the natural world, and the health consequences of ecologically injudicious behavior. Sustainability issues are of course not limited to these four disciplines, but require the engagement and interdisciplinary collaboration of other social and natural sciences, engineering, and the humanities (3).

Neither mainstream demography nor economics, for the most part, incorporates sufficient appreciation of environmental criticalities into their thinking. They implicitly assume that the world is an open, steady-state system within which discipline-specific processes can be studied. Although contemporary ecology has broadened its perspectives significantly, there is a tendency to exclude consideration of both human influence and dependence on ecosystem composition, development, and dynamics. Epidemiologists focus mainly on individual-level behaviors and circumstances as causes of disease. This discounts the underlying social, cultural, and political determinants of the distribution of disease risk within and between populations, and has barely recognized the health risks posed by today’s global environmental changes.

These four disciplines share a limited ability to appreciate that the fate of human populations depends on the biosphere’s capacity to provide a continued flow of goods and services. The assumption of human separateness from the natural world perpetuates a long-standing, biblically based premise of Western scientific thought of Man as master, with dominion over Nature (4). Many disciplines still apply world views that predate current understanding of complex system dynamics and of how human evolutionary history has developed with, and helped shape,
natural phenomena (5, 6). Their intellectual legacies need to be updated and integrated within an organized scientific effort spanning a range of disciplines that are currently not in effective communication. This would provide essential input to the sustainability discourse.

Resource Imbalances

Little demographic literature addresses the role of resource imbalances as a putative root cause for some of the changes observed in fertility and regional life expectancies (7, 8). The notion of human carrying capacity (9) is generally dismissed as irrelevant (10–12), as if humans, uniquely among species, have transcended environmental dependency. It is true that humans, through cultural developments such as agriculture, trade, and fossil-fuel combustion, have increased the carrying capacity of local environments, at least in the short to medium term. We may yet raise those limits further, or we may now be seeing early evidence of having recently exceeded the global carrying capacity, new technologies notwithstanding. We do not yet know which. Meanwhile, demographers display little awareness of the likely impacts of global environmental changes on future changes in human population size (13). The recent decline in global population growth rate has been generally welcomed by demographers (though noting the attendant problems of population aging and increased dependency ratios), suggesting that, for some, the issue of sustainability is recognized. The world view of many demographers still inclines toward that of many economists in assuming a setting free of the constraints of the carrying capacity of the biosphere.

Market Choices

The role of market forces is central to modern economics, and the turnover of goods and services is considered an indicator of progress. Instead of recognizing that the human economy is a dependent subset of the biosphere, many economists still assume that economic growth and liberalization, with wealth creation, is the key to affording adequate environmental management. Environmental quality is believed to be most effectively achieved through market forces, even as social and environmental costs are “externalized.” This view also assumes that environmental change is generally incremental, thereby overlooking the time-lagged, threshold, and irreversible effects that characterize many human and ecological systems.

The growing interdisciplinary domain of environmental and ecological economics appreciates the significance of the Earth system’s functioning for human well-being, and, therefore, the need to sustain its capacity to support economic development (14, 15). The economics of complex system dynamics and its implications for sustainability have also been addressed (16). Indeed, ecological economics treats environmental sustainability and human carrying capacity as central premises for economic development (17).

Ecosystems and Human Society

Ecologists understand the structure, functioning, and interdependencies of populations and ecosystems and, increasingly, appreciate the interplay of the natural world with human systems. However, various conceptual and theoretical frameworks in ecology still disregard the connection to the human species. More integrated views from landscape ecology and systems approaches, and the greater appreciation of complex systems, critical thresholds, and the possibilities of state changes, are attracting attention (18, 19).

Over the past decade, the fledgling field of “ecosystem health” has been fostered in interdisciplinary fashion (20, 21). There is increasing recognition that humans are themselves a major force in ecosystem development and evolution. Integrative approaches to coevolving social-ecological systems have emerged (22, 23). The ongoing Millennium Ecosystem Assessment Project, funded by several international environmental-biological conventions and other international agencies, has brought together many scientists to address interdisciplinary questions relating to the current and future conditions of the world’s ecosystems and the consequences for human societies (24).

Risk of Disease

During the recent development of epidemiology as a modern discipline, populations have been increasingly viewed as aggregations of individuals exercising free choices. According- ly, contemporary epidemiology has focused on quantifying the contribution of specific individual-level factors to disease risk. However, the resurgence of infectious disease, including particularly HIV/AIDS and various other newly identified infections, has underscored the importance of population-level phenomena, including social conditions, cultural practices, and technological choices. Similarly, dramatic changes in health and life expectancy in the countries of central and eastern Europe and the former Soviet bloc, following the collapse of communism, highlight the fundamental importance of social, economic, and political conditions to population health (25, 26). Meanwhile, there is nascent recognition that climate change and other global environmental changes pose risks to human health, both now and, more so, in the future (27).

Responding to the Crisis

Addressing sustainability is more than an academic exercise. It is a vital response to a rapidly evolving crisis and should be at the top of our research agendas. The forces that oppose social change for sustainability, whether from indifference, incomprehension, or self-interest, are powerful, and neither individual scientists nor isolated scientific disciplines will suffice to change understanding and policy. Science itself needs to be fully engaged in this challenge (28). The “science of human-environment interactions” (29) and “sustainability science” have emerged over the past decade (30). A combination of inter- and transdisciplinary approaches to sustainability, unconstrained by traditional disciplinary domains and concepts, must be encouraged. Such approaches may prove difficult to achieve within conventional university departmental and purpose-built interdisciplinary centers will therefore be needed. Other support will come from interdisciplinary societies (e.g., International Association for the Study of Common Property), research institutes (e.g., Santa Fe Institute; Beijer Institute, Stockholm; National Center for Ecological Analysis and Synthesis, Santa Barbara; International Institute for Applied Systems Analysis, Vienna), and research networks [e.g., Sustainability Science network on vulnerability, Resilience Alliance, International Council for Science (ICSU) initiative on sustainability, International Geosphere Biosphere Program, and International Human Dimensions Program on Global Environmental Change]. Achieving a sufficiently intensive interdisciplinary collaboration, on a large enough canvas to meet the needs of sustainability, remains the central challenge.

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Web Resources

www.sciencemag.org/cgi/content/full/302/5652/1919/DC1
The Burden of Chronic Disease

C. G. Nicholas Mascie-Taylor1* and Enamul Karim2

The shift from acute infectious and deficiency diseases to chronic noncommunicable diseases is not a simple transition but a complex and dynamic epidemiological process, with some diseases disappearing and others appearing or re-emerging. The unabated pandemic of childhood and adulthood obesity and concomitant comorbidities are affecting both rich and poor nations, while infectious diseases remain an important public health problem, particularly in developing countries. More attention should be given to the high burden of disease associated with soil-transmitted helminths and schistosomiasis, which until recently was not considered a priority even though regular drug treatment is obtainable at relatively little cost. In developing countries, the pressing requirement is to provide an accessible and good quality health-care system, whereas industrialized countries have a major need for greater public health education and the promotion of healthy life-styles.

The burden of disease and injury attributable to undernutrition, poor water supply, poor sanitation, and inadequate personal and domestic hygiene accounts for almost 23% of the disability-adjusted life years (DALY) from all causes worldwide and for 26% of DALY in developing regions (1). International initiatives are targeted primarily at conditions that cause higher mortality (such as AIDS, tuberculosis, malaria, and vaccine-preventable diseases), but there is also a need to focus attention on controlling conditions such as soil-transmitted helminths and schistosomiasis that lead to considerable morbidity.

Until recently, it was thought that human populations were experiencing a simple epidemiological transition. This idea, first put forward by Omran (2), envisaged three stages—“the age of pestilence and famine,” “the age of receding pandemics,” and “the age of degenerative and man-made diseases”—and assumed that as infectious diseases are eliminated, chronic diseases will increase as the population ages. However, chronic diseases are emerging as a major epidemic in many nonindustrialized countries because of their association with overweight and obesity. In addition, the upsurge of infectious diseases and the emergence of new ones also casts doubt on this simple, unidirectional epidemiological process.

Emerging and Reemerging Disease

A recent review (3) suggested that 175 human pathogens (12% of those known) were emerging or reemerging and that 37 pathogens have been recognized since 1973, including rotavirus, Ebola virus, HIV-1 and HIV-2, and most recently, Nipah virus. Among the infectious vector-borne diseases, dengue, dengue hemorrhagic fever, yellow fever, plague, malaria, leishmaniasis, rodent-borne viruses, and arboviruses are persisting, and sometimes re-emerging, with serious threats to human health. For example, malaria, which is the foremost vector-borne disease worldwide, continues to worsen in many areas, and there are now an estimated 300 million to 500 million cases of malaria worldwide each year with 2 million to 4 million deaths. Since 1975, dengue fever has surfaced in huge outbreaks in more than 100 countries, with as many as 100 million cases each year. These increases reflect societal changes arising from population growth, ecological and environmental changes, and especially suburbanization, together with widespread and frequent air travel.

The prevalence of obesity, with its known increased risk of developing chronic ailments, some forms of cancer, type 2 diabetes, and cardiovascular disease, is increasing in most countries. It is estimated that more than 1 billion adults worldwide are overweight and that 300 million are clinically obese. In the United Kingdom, obesity has tripled in the past 20 years, and about two-thirds of adults are overweight.

In the United States, 20 states have obesity prevalence rates of 15 to 19%, 29 have rates of 20 to 24%, and one has a reported rate of more than 25%. Overweight and obesity are not confined to adults, and there is evidence of an increase in the prevalence of childhood overweight and obesity in both developed and developing countries.

Helminths and Morbidity

Infection by soil-transmitted helminths has been increasingly recognized as an important public health problem, particularly in developing countries. Parasitic infection accounts for an estimated 22.1 million life years lost to hookworm (either Necator americanus or Ankylostoma duodenale), 10.5 million life years lost to roundworm (Ascaris lumbricoides), 6.4 million life years lost to whipworm (Trichuris trichiura), and 4.5 million life years lost to schistosomiasis (4). These figures take into account the range of morbidity associated with these infections and with hookworm-induced anemia. The total for all three soil-transmitted infections and schistosomiasis is 43.5 million life years lost, which is second only to tuberculosis (46.5 million) and well ahead of malaria (34.5 million) and measles (34.1 million).

Worm transmission is enhanced by poor socioeconomic conditions, deficiencies in sanitary facilities, improper disposal of human feces, insufficient supplies of potable water, poor personal hygiene, substandard housing, and lack of education [hence intestinal parasitism’s label as the “disease of poverty” (5)]. About 25% of the world’s population are infected with roundworm, 20% with hookworm, 17% with whipworm, and 3 to 4% with schistosomes (Table 1), and overall ~2 billion people worldwide (a third of the world’s population) are affected with one or more of these soil-transmitted infections and schistosomiasis (6).

The estimated worldwide percentages of the three intestinal parasites have remained relatively constant (7). The lifetime risk of infection with hookworm is approximately 90% in the tropics and 50% in temperate climates (8). Among the hookworm species, N. americanus is prevalent in the Americas, while A. duodenale is common in the Mediterranean (9). The prevalence of whipworm infection is highest in South-Central Africa, with a peak of ~80% in Chad (10). The global prevalence of hookworm and whipworm infections is 23% and 12%, respectively (Table 1), while 7% of the global population is infected with schistosomiasis (11). The most common species is Schistosoma mansoni, with a prevalence of 4% (12). In Africa, 45 million people suffer from schistosomiasis, with 10 million of them, mostly children, being severely affected (13).

Table 1. Estimated global prevalences and associated morbidity and mortality due to soil-transmitted helminths and schistosomes.

<table>
<thead>
<tr>
<th>Parasite</th>
<th>Prevalence of infection (cases, millions)</th>
<th>Mortality (deaths, thousands)</th>
<th>Morbidity (cases, millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascaris lumbricoides</td>
<td>1450</td>
<td>60</td>
<td>350</td>
</tr>
<tr>
<td>Trichuris trichiura</td>
<td>1050</td>
<td>10</td>
<td>220</td>
</tr>
<tr>
<td>Hookworms</td>
<td>1300</td>
<td>65</td>
<td>150</td>
</tr>
<tr>
<td>Schistosomes</td>
<td>200</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
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T R A G E D Y O F T H E C O M M O N S ?

V I E W P O I N T

S P E C I A L S E C T I O N

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nearly constant over the past 50 years (7), but there have been some successes. For example, in Japan, intestinal helminth infections were virtually wiped out in a 15- to 20-year period after World War II through an integrated program of education, improved sanitation and water supply, and drug treatment (8).

What has changed over the past 25 years, however, is the recognition that these soil-transmitted helminth infections and schistosomiasis have serious health consequences ranging from reversible growth faltering, permanent growth retardation, clinically overt symptoms (e.g., nausea, diarrhea, dysentery, and fever) to acute complications (e.g., intestinal obstruction; rectal prolapse; granulomas in the mucosa of the urogenital system, intestine, and liver; cancer of the bladder; hepatomegaly; and ascites). These parasitic infections are associated with malnutrition and impaired growth and development (caused by decreased appetite, nutrient loss, malabsorption, and decreased nutrient utilization), iron deficiency anemia (the blood-sucking activities of hookworm leads to blood loss of between 0.03 and 0.15 ml per day per worm), decreased physical fitness and work capacity, and impaired cognitive function (9–11).

The formal recognition of the health consequences of worm infestation came as recently as May 2001 when the 54th World Health Assembly passed a resolution affirming that the control of schistosomiasis and soil-transmitted helminthiasis should be considered as a public health priority. The challenge ahead is converting words into deeds through a global helminth control program (12).

Global Helminth Control

Horton (13) calculated that ~500 million children will have to be treated regularly for ascariasis for the next 25 years for the absolute numbers to stay the same. However for a reduction to occur, at least 1 billion will need regular treatment. This figure is for ascariasis alone; to treat all soil-transmitted infections and schistosomiasis would require doubling this number. Furthermore, there is evidence of drug resistance in animals in which intensive helminth control measures have been used, and some concerns have been expressed that the same might happen with humans, although extrapolation from animals raised for food production to humans must take into account genetic and epidemiological differences (14). There are already indications that schistosomiasis cure rates (using praziquantel) are worse than those a decade ago (15), and mebendazole and pyrantel may be less effective against hookworm now than in the past (16, 17). No alternatives exist to praziquantel, but using combinations of drugs or cycling their use may reduce drug resistance.

At first sight, the drug and infrastructure cost of global helminth control appears enormous. For example, the cost of drugs alone in treating 2 billion people annually will be about US$100 million. This sum, although large, has to be seen within the context of worldwide health expenditure per capita, which ranges between about US$12 and US$2769 (18), whereas the cost of a single-dose anthelmintic treatment is only about US$.03 per annum (and about US$.20 to US$.30 for praziquantel), excluding delivery costs (19).

The current laudable goal of helminth control is very different from the earlier, but disastrous, attempts at hookworm and malaria eradication. So far only smallpox has been eradicated (1980), but the World Health Organization is also committed to eradicating poliomyelitis (by 2005) and dracunculiasis (guinea worm), and a global lymphatic filariasis campaign has also commenced (20). The dracunculiasis eradication campaign (21) began in 1980, and the incidence fell from an estimated 3.2 million cases in 1986 to 64,000 cases in 2001. More than 150 countries and territories have been certified free of parasite transmission, and the eradication goal is in sight. However, programs are being disrupted, particularly in countries affected by civil conflict, such as Sudan, where ~78% of the world’s cases were reported in 2001.

Global Health Trajectories and Solutions

The health and disease patterns of societies and countries evolve as a result of socioeconomic, demographic, technological, cultural, environmental, and biological changes. Wars and civil conflict continue to disrupt the human host-agent-environment equilibrium and elevate disease burden, while injuries caused by accidents and violence are also increasing.

So is “Health for All in the 21st Century” (22) any closer? The industrialized countries appear to be exchanging one enemy for another: Having in the main brought infectious diseases under control, the unbounded increase in obesity in childhood and adulthood and its concomitant comorbidities are likely to result in massive social and economic burdens. Only with dramatic changes in life-style—decreases in physical portion sizes, energy density of the diet, and fat intake, and increases in fruit and vegetable consumption and physical activity—can obesity and the metabolic syndrome epidemic be brought under control. Successful strategies involve governments and local communities working together to initiate programs in schools, the workplace, and communities (23) and should involve food producers, the food-processing industry, and consumer associations.

Improving the health status of poor populations requires a twin approach. Not only are infectious diseases still common, but chronic diseases, including tobacco-related diseases, are on the rise. Many of the poorer countries lack accessible, affordable, and high quality health-care systems. Strengthening national health policies, managing and mobilizing resources, training personnel, and providing service delivery are key goals. Developing public health strategies at national and global levels and financing and organizing them will continue to present enormous challenges (24).

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The Challenge of Long-Term Climate Change


Climate policy needs to address the multidecadal to centennial time scale of climate change. Although the realization of short-term targets is an important first step, to be effective climate policies need to be conceived as long-term programs that will achieve a gradual transition to an essentially emission-free economy on the time scale of a century. This requires a considerably broader spectrum of policy measures than the primarily market-based instruments invoked for shorter term mitigation policies. A successful climate policy must consist of a dual approach focusing on both short-term targets and long-term goals.

There is widespread consensus in the climate research community that human activities are changing the climate through the release of greenhouse gases, particularly CO₂, into the atmosphere (1–2). Because of the considerable inertia of the climate system—caused by the long residence times of many greenhouse gases in the atmosphere, the large heat capacity of the oceans, and the long memory of other components of the climate system, such as ice sheets and the biosphere—human modifications of the climate system through greenhouse gas emissions are likely to persist for many centuries in the absence of appropriate mitigation measures (2).

A common response to the uncertain risks of future climate change is to develop climate policy as a sequence of small steps. The Kyoto protocol, once enacted, will commit the signatories to a nominal reduction of greenhouse gas emissions by 5% between 2008 and 2012, relative to 1990. The protocol is a historic first step toward reversing the trend of continually increasing greenhouse gas emissions and will provide valuable experience in the application of various mitigation instruments such as tradable emission permits. However, a nominal emission reduction of only 5% by a subset of the world’s nations will have a negligible impact on future global warming. To avoid major long-term climate change, average per capita greenhouse gas emissions must be reduced to a small fraction of the present levels of developed countries on the time scale of a century (2).

Such reductions cannot be achieved by simply extrapolating short-term policies but require a broader spectrum of instruments.

Most investigations (2–4) and public attention have focused on the projected climate change in this century. A potentially far more serious problem, however, is the global warming anticipated in subsequent centuries if greenhouse gas emissions continue to increase unabated (Fig. 1, left panels) (5–7). The projected temperature and sea level changes for the next millennium greatly exceed those in the next hundred years (Fig. 1, yellow boxes). If all estimated fossil fuel resources are burnt, CO₂ concentrations between 1200 parts per million (ppm) (scenario C in Fig. 1) and 4000 ppm (scenario E in Fig. 1) are predicted in the second half of this millennium, leading to temperature increases of 4°C to 9°C and a sea level rise of 3 to 8 m. Predictions of this magnitude are beyond the calibration ranges of climate models and must therefore be treated with caution (8).

However, the predicted climate change clearly far exceeds the natural climate variability (±1°C to 2°C) experienced in the past 10,000 years. Even if emissions are frozen at present levels, the accumulated emissions over several centuries still yield climate change on the order of the lower business-as-usual (BAU) scenario C.

Major climate change can be avoided in the long term only by reducing global emissions to a small fraction of present levels within one or two centuries. As an example, we have computed optimal CO₂ emissions paths that minimize the time-integrated sum of climate damage and mitigation costs, using an integrated assessment model consisting of a nonlinear impulse response climate model (7) coupled to an elementary economic model (9) (Fig. 1, right panels). Cost-benefit analyses depend on many controversial assumptions, such as the role of economic inertia (included in case a, ignored in case b), the impact of declining costs for new technologies, and the discount factors applied to future climate change mitigation and adaptation costs (10–14). However, the resultant long-term climate change is insensitive to the details of the optimal emission path (compare curves a and b), provided the emissions are sufficiently reduced. Because of the long residence time of CO₂ in the atmosphere (>100 years), the climatic response is governed by the cumulative CO₂ emissions rather than by the detailed path.

The impact of the Kyoto agreement (k in Fig. 1, right panels) is hardly discernible on the millennial time scale, suggesting that the Kyoto debate should focus on the long-term implications of the protocol rather than on its short-term effectiveness. The Kyoto targets may not be met by some countries and may be exceeded by others. Important in either case is that the Kyoto policy is accompanied by measures that ensure continuing reductions in subsequent decades.

Because of the 10-year horizon of the Kyoto protocol, climate policy has tended to focus on promoting mitigation technologies that are currently most cost-effective, such as wind energy, biomass fuels, fuel switching from coal and oil to gas, and improved energy efficiency in transportation, buildings, and industry. In the short to medium term, the combined mitigation potential of these technologies is substantial: It has been estimated that, if fully implemented, they could halve global greenhouse gas emissions relative to the BAU level within two decades (4). The market-based instruments (such as tradable emission permits and tax incentives) used to meet the more modest 5% Kyoto reduction targets will accelerate the penetration of these technologies into the marketplace but will be inadequate to realize the full potential of these technologies.

Yet, even if forcefully implemented, currently available low-cost technologies have limited capacity for substantial global emission reduction and will not be able to counter the rising emissions projected for the long term. Future emissions will be driven mainly by the expanding populations of the developing world, which strive to achieve the same living standards as the industrial countries. An emissions reduction of 50% applied to a projected BAU increase in this century by a factor of four (2–4) still leads to a doubling of emissions, far from the long-term target of near-zero emissions. Furthermore, the mitigation costs for today’s technologies are estimated to rise rapidly if per capita emissions are reduced by more than half (4). Thus, although the Kyoto protocol will

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boost technologies that are cost-effective in the short term, further emission reductions in the post-Kyoto period could be limited by prohibitive costs. Without affordable new technologies capable of higher global emission reductions, stricter emission reduction targets will be considered impossible to meet and will not be adopted.

Although no such technology is yet economically competitive, there exist many promising candidates (15, 16), ranging from solar thermal or photovoltaic energy—in combination with hydrogen technology—to carbon sequestration in geological formations or the ocean (17–20), advanced nuclear fission, and nuclear fusion (4, 15, 16). Which technology, or mix of technologies, will ultimately prove most cost-effective cannot be predicted. We will need to accept these uncertainties and support a number of competing technologies in order to have available several commercially viable alternatives when the large-scale transition to low-emission technologies becomes more urgent.

Although short-term climate policy can be formulated in terms of emission targets and implemented with instruments that internalize the costs incurred by climate change (“polluter-pays principle”), long-term climate policy will require a broader spectrum of measures extending well beyond the traditional horizon of government policies or business investment decisions. The entry of new technologies into the marketplace depends on multiple incentives and feedbacks, including private investments; government investments in infrastructure and subsidies for pilot plants; protected niche markets; and changes in consumer preferences and lifestyles (21–23). Climate is a public good that demands communal action for its protection, including the involvement of citizens and institutions such as the media that shape long-term public attitudes. Self-interest alone will not motivate businesses and the public to change established practices and behavioral patterns. The goal of long-term climate policy must be to influence business investments, research, education, and public perceptions such that stringent emission-reduction targets—although not attainable today—become acceptable at a later time.

Although major changes are necessary, the long time scales of the climate system allow a gradual transition (24, 25). Estimated costs to halve global emissions range from ~1 to 3% of gross domestic product (GDP) (4), similar to the annual GDP growth rate in many countries. Thus, implementation of an effective climate policy over a time period of, say, 50 years would delay economic growth by only about a year over the same period (26). This appears to be an acceptable price for avoiding the risks of climate change. However, because the global political-economic system exhibits considerable inertia, a transition to a sustainable climate can be achieved without major socioeconomic dislocations only if the introduction of appropriate measures addressing the long-term mitigation goals is not delayed.

Science can assist the development of long-term climate policies by providing detailed analyses of the technological options and their implications for national economies and global development. The Intergovernmental Panel on Climate Change (IPCC) has played a pivotal role in the climate debate by presenting authoritative reviews of the state of science and on climate change impact, mitigation, and policy. Similar expertise should be made available to climate negotiators in the form of timely analyses of the implications of alternative climate policy regimes for the individual signatories of the United Nations Framework Convention on Climate Change. Although binding long-term commitments cannot be expected from governments, declarations of long-term policy goals and visible actions to achieve these goals are essential for the investment plans of businesses, particularly for energy technologies characterized by long capital lifetimes. A long-term perspective is equally important for the public, who must understand and support the policies. Binding commitments to meet short-term emission-reduction targets must therefore go hand in hand with clearly defined strategies to achieve substantially more stringent reductions in the longer term.

Fig. 1. $CO_2$ emissions and concentrations, global mean near surface temperature, and global mean sea level for business-as-usual (BAU) emission scenarios (left) and optimized cost/benefit (C/B) trajectories (right; note change of scale). The BAU scenarios assume that all fossil fuel resources ranging from 4000 gigatons of carbon (GtC) (conventional resources, C) to 15,000 GtC (conventional plus exotic resources, E), are used. The sea level rise represents the sum of thermal expansion of the warming ocean, the melting of smaller inland glaciers, and the slow melting of the Greenland Ice Sheet (1). Inclusion of other greenhouse gases could increase the peak values by ~10 to 20%. The cost/benefit solutions include (a) or ignore (b) economic inertia. Pronounced differences between these cases in the short term have little impact on long-term climate. The impact of the Kyoto period (k) is not discernible on these multidecadal time scales.
Human-induced climate change is one of the most important environmental issues facing society worldwide. The overwhelming majority of scientific experts and governments acknowledge that there is strong scientific evidence demonstrating that human activities are changing the Earth’s climate and that further human-induced climate change is inevitable. Changes in the Earth’s climate are projected to adversely affect socioeconomic systems (such as water, agriculture, forestry, and fisheries), terrestrial and aquatic ecological systems, and human health. Developing countries are projected to be most adversely affected, and poor people within them are the most vulnerable. The magnitude and timing of changes in the Earth’s climate will depend on the future demand for energy, the way it is produced and used, and changes in land use, which in turn affect emissions of greenhouse gases and aerosol precursors.

The most comprehensive and ambitious attempt to negotiate binding limits on greenhouse gas emissions is contained in the 1997 Kyoto Protocol, an agreement forged in a meeting of more than 160 nations, in which most developed countries agreed to reduce their emissions by 5 to 10% relative to the levels emitted in 1990. Although the near-term challenge for most industrialized countries is to achieve their Kyoto targets, the long-term challenge is to meet the objectives of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), i.e., stabilization of greenhouse gas concentrations in the atmosphere at levels that would prevent dangerous anthropogenic interference with the climate system, with specific attention being paid to food security, ecological systems, and sustainable economic development. To stabilize the atmospheric concentration of carbon dioxide requires that emissions eventually be reduced to only a small fraction of current emissions, i.e., 5 to 10% of current emissions.

All major industrialized countries except the United States, the Russian Federation, and Australia have ratified the Kyoto Protocol. The United States and Australia have publicly stated that they will not ratify it, and statements from the Russian Federation are contradictory. Russian ratification is essential for the Kyoto Protocol to enter into force.

The United States has stated that the Kyoto Protocol is flawed policy for four reasons:

1) There are still considerable scientific uncertainties. However, although it is possible that the projected human-induced changes in climate have been overestimated, it is equally possible that they have been underestimated. Hence, scientific uncertainties, as agreed by the governments under Article 3 of the UNFCCC, are no excuse for inaction (the precautionary principle).

2) High compliance costs would hurt the U.S. economy. This is in contrast to the analysis of the Intergovernmental Panel on Climate Change (IPCC), which estimated that the costs of compliance for the United States would be between US$14 and US$135 per ton of carbon avoided with international carbon dioxide emissions trading (a 5-cents-per-gallon gasoline tax would be equivalent to US$20 per ton of carbon). These costs could be further reduced by the use of carbon sinks, by carbon trading with developing countries, and by the reduction of other greenhouse gas emissions.

3) It is not fair, because large developing countries such as India and China are not obligated to reduce their emissions. However, fairness is an equity issue. The parties to the Kyoto Protocol agreed that industrialized countries had an obligation to take the first steps to reduce their greenhouse gas emissions, recognizing that ~80% of the total anthropogenic emissions of greenhouse gases have been emitted from industrialized countries (the United States currently emits ~25% of global emissions); that per capita emissions in industrialized countries far exceed those from developing countries; that developing countries do not have the financial, technological, or institutional capability of industrialized countries to address the issue; and that increased use of energy is essential for poverty alleviation and long-term economic growth in developing countries.

4) It will not be effective, because developing countries are not obligated to reduce their emissions. It is true that long-term stabilization of the atmospheric concentration of greenhouse gases cannot be achieved without global reductions, especially given that most

References and Notes
8. The uncertainties of climate predictions are estimated to be ~50%, excluding instabilities of the climate system that could yield substantially larger changes, for example, through the collapse of the Gulf Stream and deep ocean circulation system, a break-off of the West Antarctic ice sheet, or the release of methane presently frozen in permafrost regions.
22. O. Edenhofer et al., in preparation.

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Climate Change: The Political Situation

Robert T. Watson

T R A G E D Y  O F  T H E  C O M M O N S ?

VIEWPOINT
of the projected growth in greenhouse gas emissions over the next 100 years is from developing countries. Hence, developing countries will have to limit their emissions of greenhouse gases, but industrialized countries should take the lead, as agreed in Kyoto.

Protection of the climate system will require substantial reductions in greenhouse gas emissions; hence, the Kyoto Protocol is recognized to be only the first step on a long journey to protect the climate system. However, unless the United States agrees to meaningful reductions in greenhouse gas emissions, it is highly unlikely that major developing countries will agree to limit their emissions or that industrialized countries will agree to further reductions beyond those already agreed in Kyoto.

One very positive development is that about half of the U.S. states have enacted some climate protection measures, and there are a number of initiatives in the U.S. Congress that would reduce greenhouse gas emissions. Although the McCain-Lieberman Climate Stewardship Act failed to pass in the Senate, 43 senators did vote for it, demonstrating an increasing recognition by members of Congress that there is an urgent need to deal with the climate issue. In addition, more than 40 multinational companies have voluntarily agreed to reduce their emissions of greenhouse gases and to improve the energy efficiency of their products. Several of these companies have already met or exceeded their initial targets and have saved money in doing so.

Technologies exist or can be developed to cost-effectively limit the atmospheric concentration of carbon dioxide to between 450 and 550 parts per million (ppm), but it will take political will, enhanced research and development activities, public-private partnerships, and supporting policies to overcome barriers to the diffusion of these technologies into the marketplace. A number of countries, including the United States, have committed themselves to developing climate-friendly technologies, but the level of investment must be substantially increased. The Kyoto Protocol needs to be ratified, and the United States needs to take meaningful actions to reduce its greenhouse gas concentrations. Governments should then consider setting a long-term target based either on a greenhouse gas stabilization level (between 450 and 550 ppm) or on limits for both the absolute magnitude of global temperature change (less than 2 to 3°C) and the rate of temperature change (less than 0.2°C per decade). A series of intermediate targets can then be developed to involve developing countries in an equitable manner. The need to reduce greenhouse gas emissions offers a unique opportunity to modernize energy systems and enhance competitiveness in a globalized world.

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Tales from a Troubled Marriage: Science and Law in Environmental Policy

Oliver Houck

Early environmental policy depended on science, with mixed results. Newer approaches continue to rely on science to identify problems and solve them, but use other mechanisms to set standards and legal obligations. Given the important role that science continues to play, however, several cautionary tales are in order concerning "scientific management," "good science," the lure of money, and the tension between objectivity and involvement in important issues of our time.

“The scientific debate remains open. Voters believe that there is no consensus about global warming within the scientific community. Should the public come to believe that the scientific issues are settled, their views about global warming will change accordingly. Therefore, you need to continue to make the lack of scientific certainty the primary issue in the debate...” [Frank Luntz, political strategist, 2002 (I)].

This essay explores the relationship between science and law in environmental policy. The relationship has not been easy, nor has it achieved closure after more than 30 years of marriage. Two alpha partners are still trying to figure out who does what. Both agree on the importance of an environmental policy. The debate is about what it should be based on and how it should be carried out.

Back in the pre-dawn of public environmental statutes, there were private remedies for environmental harms, in tort and nuisance. If someone contaminated your apple orchard, or your child, you could seek damages and even an injunction against the activity. These remedies proved insufficient for at least two reasons. The first is that a civil law response to harm already done is small solace for someone who has lost her livelihood or the health of her child. The second is illustrated by the real-life saga described in A Civil Action, involving the contamination of drinking water from, in all probability, industrial waste sites (2). Children died, others were rendered vegetables for life, and their parents suffered a grief that is impossible to describe. But their legal case failed, as many others did, over the requirements of proof and causation. Which chemical, of the many toxicins in the waste sites, caused these strange infirmities and through exactly what exposure pathways? Which waste sites were responsible: this one, operated by a company with lawyers on tap and a war chest of money available for its defense; or that one, now abandoned, once owned by a corporation long dissolved? Civil law failed because the science could not make the proof.

First-Generation Environmental Law: Science Embraced

Beginning in the 1960s, Congress surmounted these difficulties with new public environmental statutes, each based on standards of performance. The standards would operate by preventing rather than compensating for harm. They would, further, bypass the rigors of causation and proof: Once a standard was set, one had only to see whether or not it was met. The question remained, however: Who would set the standard? The answer seemed apparent. Scientists would, on the basis of scientific analysis. After all, it was the scientists, such as Rachel Carson, Jacques Cousteau, and Yuri Timoshenko, who had sounded the alarm; they were the ones to put out the fire.

The first wave of environmental law, therefore, was science-based environmental policy in action. One of the first was the Water Quality Act of 1965 (3), which sought the attainment of water quality criteria. It was soon followed by the National Environmental Policy Act of 1969 (4) and the analysis of environmental impact. Then came the Clean Air Act in 1970 (5), focused on the attainment of national ambient air quality stan-
...disposal) (6), the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (abandoned waste sites) (7), the Toxic Substances Control Act (TSCA) (chemicals) (8), the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (pesticides) (9), and the Safe Drinking Water Act (10), all with the same premise: Science would tell us what was safe and what was not. Scientists would draw the lines.

It didn’t work. None of these laws worked well, and some, after enormous investment, failed utterly (11). We began to realize that science, although endlessly fascinating and constantly revelatory, is rarely dispositive. And in the world of environmental policy, that which is not dispositive is dead on arrival. The reason is political: Environmental policy faces a degree of resistance unique in public law. No one who has to comply with environmental law likes it, and many hate it outright. A conventional explanation is money, and that is certainly a factor; it takes more capital to install pollution controls or to raise the causeway on stilts. Environmental law is also intrusive: It involves other people, state bureaucrats for one, in the operation of your oil refinery, pig farm, or real estate portfolio. Worse, it puts the general public in there too, nosing around, asking questions, taking their complaints to the media. They interfere with your personal life as well: your commuter highway, your garbage, or the way your granddaddy ran cattle and you’ve always run cattle in your family. These are life choices; often life values. Read George Will (12), listen to Rush Limbaugh (13). For some, environmental policies seem to threaten their very soul.

Not far from the bottom of all of this resistance is one more element: the embarrassment factor. No one likes to be tagged with the responsibility for poisoning children with lead or destroying the Everglades, and a small industry of euphemisms has sprung up to mask the blame. Strip mining becomes “the removal of overburden,” as if the soil, grass, and trees were somehow oppressing the land; dredgers in Louisiana leave “borrow pits,” as if they were going to give the soil back someday. At the top of the 2002 domestic agenda are the “clear skies” and “forest health” initiatives (14), labels that at the least disguise the contents of these programs, if not belie them. This is embarrassment speaking.

The extraordinary degree of resistance to environmental policy brings at least two consequences. First: That which is not nailed down by law is not likely to happen. Second: Even requirements that are nailed down by law, such as the permit requirements of the Clean Water Act or the no-jeopardy standard of the Endangered Species Act (ESA), secure compliance rates of about 50% percent (15). A good rule of thumb is that no environmental law, no matter how stringently written, achieves more than half of what it set out to do.

With this understanding of the special challenges of environmental policy, it is easy to see why science-based approaches fare so poorly. One lesson in this regard can be drawn from the Federal Water Pollution Control Act, aimed at the attainment of water quality standards. Scientists would establish concentration limits for every pollutant, and when waters exceeded these limits, scientists would determine the cause and require abatement. But concentration limits for what use: swimming, drinking water, or fishing? If for fishing, would the target be catfish or trout, which have widely differing requirements for dissolved oxygen? And for the lower Mississippi River, which basically floats boats, why would one need fish at all? The first question in the standard-setting process, then, depended on identifying goals that were purely political and that, as Congress later found, led inexorably to a race to the bottom: States lowered their standards to attract industry, which then held them hostage under the threat of moving away (16).

The “scientific” part of the act was equally fluid. It involved extrapolating “acceptable” concentration limits from laboratory experiments to natural surroundings; from single pollutants to cocktails of multiple pollutants; and from rapid, observable, lethal effects to long-term, sublethal, and reproductive effects. Then came dilution factors, fate, and dispersion and mixing zones. Conclusions differed by factors of 10, scientist against scientist. When it came next to enforcement, someone had to prove who and what were causing the exceedance of the standards. If Lake Pontchartrain turned en tropic, was it the cattle farming, the shoe tannery, the local sewage system, or Mother Nature? The higher the stakes, the more contested the science. The problem was not information, it was closure. We had returned to the difficulties of A Civil Action. Whether in tort law or public law, the proofs failed.

Environmental statutes addressing toxicity record the problem in a more acute form. In the early 1970s, a number of laws were enacted based on determinations of “unreasonable risk to human health in the environment” (17). The challenges to scientists here were even more demanding. How were they to determine risk to human health, except through experiments with rodents? But what was the dose-response relationship in a rat, and what was the relationship of a rat to a human, and were these relationships linear, curved, parabolic . . . who knew? Further, exactly which humans were they to consider: those living at the fence line, elderly asthmatics, kids sneaking in to play in the dirt, or fishermen downstream of the outfalls of pulp and paper mills who were eating residues of dioxin in their catch? Were they eating the bodies of the fish or the heads, and were they frying them or stewing them raw? What would scientists do, moreover, about toxins, including many carcinogens, for which they could establish no known threshold of safety? And finally, even if they could arrive at a scientific-looking determination of risk (18), what risk level was acceptable: one death in ten thousand, one in a million? The dioxin standards for the states of Minnesota and Virginia, for exactly the same dischargers, differ by more than a thousand times (19).

Facing these difficulties, and with each of their decisions subject to legal challenges, the toxic programs of the air, water, pesticide, and related laws fell into a swoon. Mountains of paper spanning decades produced only a handful of standards, against a backdrop of thousands of toxic substances. Some of the biggest actors—lead, polychlorinated biphenyls (PCBs), trichloroethene (TCEs), and dioxins to this day—stalled out and were only moved forward through litigation or overwhelming public outcry. For the opponents of these standards, there was always an unexplored factor. That is the essence of science. Meanwhile, global temperatures are rising. Parts of the Arctic ice shelf are breaking off into the sea.

Perhaps the most celebrated mess in environmental policy is the Superfund program, whose cleanups run into millions of dollars per site (20). The actual money expended on the cleanup is only part of that sum; a major amount is spent on the science-based determination of “how clean is clean.” The disputes, uncertainties, and costs of this approach led Judge Steven Breyer, now a justice of the U.S. Supreme Court, after just one trial of a Superfund cleanup, to write a book calling for the establishment of an unreviewable panel of scientific experts to decide these questions once and for all (21).

Second-Generation Environmental Law: Science Rejected

Fortunately, Congress did not buy Judge Breyer’s suggestion. It took a different route. As a result, air emissions, water emissions, and toxic discharges have plummeted, for some industries all the way down to zero. In 1972, after 15 years of futility with the water quality standards program, during which the Cuyahoga River and the Houston Ship Canal caught fire; lakes the size of Erie were declared dead; fish kills choked the Chesapeake Bay; and Louisiana’s Secretary of Agriculture declared Lake Providence, poisoned by the pesticide toxaphene, safe for humans so
The theory of BAT was very simple: If emissions could be reduced, just do it. It did not matter what the impacts were. It did not matter whether the plant was discharging into Rock Creek, the Potomac River, or the Atlantic Ocean. It didn’t matter what scientists said the harm was or where it came from (24). Just do it. Within 5 years, industrial discharges of conventional pollutants were down by 80% in most industrial categories (25). Receiving water quality improved by an average of 35% across the board (26). For all BAT-controlled sources, the amendments were a stunning success. Permit writers no longer had to deal with dueling scientists, mounds of impenetrable data, or the pressures of local politics. Once the technology was identified, they had their discharge limit. Compliance was equally straightforward. Even a judge could see it. That made the policy enforceable, and that made it law, and that meant it would happen.

The concept of BAT was the “Eureka!” moment in environmental law. Imitation is a measure of success, and other laws were adopted BAT (best available technology) (27). The Clean Air Act adopted MACT (maximum achievable control technology) (28). Natural resources law followed suit as well, with alternative-based requirements providing clear and enforceable protections for historic sites, parks, endangered species, wetlands, and the coastal zone (29). We were no longer trying to calibrate harm. We were requiring alternatives-based solutions.

This said, BAT was no panacea. It bred its own resistance and some industries, through prolonged lawsuits (best available litigation), managed to stave off its application for decades (30). BAT also had its own Achilles heel, to be found in how one defined the scope of the proposal. If discharges from pulp and paper mills were at issue, for example, the most obvious way to avoid dioxin residues would be to eliminate the use of chlorine, but if the scope were reduced to pulp mills using chlorine bleach, then the use of chlorine and residues of dioxin were a given. Likewise, if the dredging of clam shells from Lake Pontchartrain was viewed as a search for clam shells, then there was no alternative to the dredging and BAT failed.

For these reasons, all approaches became necessary in cutting the Gordian knot: engineer- ing, science, tort actions, and, more recently, economic and market incentives. Each approach has its spearheads. The National Resources Defense Council has focused for decades on advancing BAT requirements. Environmental Defense, on the other hand, specialized in science-based litigation over DDT, PCBs, and pesticides and has since taken the lead on economic incentives. Toxic tort actions continue to drive polluters toward abatement, if only as a defense against claims of negligence, and have helped run to ground actors as large as the pulp and paper industry, maritime shipping, and tobacco. There is no longer one way, there are many; and science is no longer king.

Science still, however, plays lead roles. One is to sound the alarm, as it has done for decades and done recently regarding ozone thinning, climate change, and the loss of biolog- ical diversity. It is up to science as well to provide a rationale (for example, heavy metals are bad for you) for the requirement of BAT; we cannot BAT the world. It also falls to science to identify substances that are so noxious (bioaccumulative toxins, for example) that they need to be phased out completely, BAT be damned (31). Science-based standards play a similar role in federal air and water quality programs: a safety net in situations where, even with the application of BAT or MACT, air and water quality remain unsafe for human health and the environment (32). Scientists play the same, and in this case dispositive, role under the ESA, defining a baseline—jeopardy—above which no further impacts will be allowed (33). Last but not least is the job of restoration, be it the cleanup of contaminated aquifers, the recovery of the endangered Palila, or the reassembly of eco-systems the size of the Chesapeake Bay and the Louisiana coastal zone.

**Four Cautionary Tales**

With such power and so much riding on the opinions of scientists, however, four notes of caution are in order.

The first is beware the lure of a return to “scientific management.” The technology standards that brought environmental programs out of their stalemate toward success were criticized from day one, and remain criticized today, as “arbitrary,” “one size fits all,” “inflexible,” and “treatment for treatment’s sake,” outmoded in today’s world. What we need, goes the song, is “iterative,” “impact-based,” “localized” management focused on the scientifically determined needs of this river, that airshed, this manufacturing plant, or that community. It sounds as attractive and rational as it did 40 years ago, but we have tried that for decades and failed. The largest loss leaders of the federal air and water quality acts are the science-based TMDL (total maximum daily load) (34) and SIP (state implementation plan) (35) programs, which eat up heroic amounts of mon-
demics in the sciences receive their salaries and technical support through grants and outside funding, nearly a third of it from industry. Their promotions and tenure are based on the amounts of money they bring in. In 1998, the New England Journal of Medicine published an article with the unremarkable but statistically documented conclusion that there was a “significant difference” between the opinions of scientists who received corporate funding and those who did not, on the very same issues (42). Hearing this, do we fall over with surprise? To put it crudely, money talks, and among scientists, the money is too often hidden. Even the conclusions can be hidden, if they are unwelcome to the sponsors. On important public issues, the public never knows.

A final caution is the lure of the “safe” life, the apolitical life, free from the application of what scientists know to the issues around them. One must respect anyone’s liberty to choose to be a player or not, and the additional need of the profession for the appearance and fact of objectivity. The question is, notwithstanding: Given the pressure of environmental issues today and their dependence on science, can scientists afford to sit it out? As we speak, an increasing number of scientists are being pulled off of studies, sanctioned, and even dismissed for conclusions that contradict the ideology of their bosses (43). This question does not concern who pays for what conclusions. It concerns a duty to act and to defend your own.

In the early 1990s, the so-called Contract with America (44) identified a series of laws to be amended or repealed, many of which were environmental. At the top of the list was the ESA. As Speaker of the House Newt Gingrich began work to implement the contract, the ESA was in serious trouble. Gingrich was also, however, an intellectual who at least enjoyed a good discussion. More than that, he harbored a lifelong passion for zoos. Concerned about the fate of the ESA, the curator of the Atlanta zoo, an acquaintance of Gingrich, suggested to him that he have a chat with E. O. Wilson. Gingrich accepted, and Wilson came to Washington along with two other icons of the natural sciences, Thomas Eisner and Stephen J. Gould. It was a long meeting. They agreed to meet again. Over time, Gingrich would assure these scientists that nothing would happen to the ESA that did not have their review and, more extraordinarily, their approval.

It was not an easy promise to keep. The pressure on Gingrich from leaders of his own party was intense. He met again with Wilson et al. They held the line. The 104th Congress wound down with two extremely hostile bills out of committee, waiting only for their moment on the floor, which never came. It was a critical moment in environmental policy. It was also a true marriage of science and law.

References and Notes
1. For a complete text of the memorandum, see www.luntspeak.com/meemo4.html.
4. 42 U.S.C. §§ 7431 et seq.
5. 42 U.S.C. §§ 7401 et seq.
8. 7 U.S.C. §§ 136a-4 et seq.
9. 42 U.S.C. §§ 500 g-1 et seq.
14. For the results of federal agency consultations under the ESA, see O. A. Houck, Colorado Law Rev. 64, 277 (1993); for the similar results of the Clean Water Act, see R. W. Adler, The Clean Water Act 20 Years Later (Island Press, Washington, DC, 1993).
15. For the misleading appearance of scientific objectivity, can scientists afford to sit it out? As we speak, a growing number of scientists are being pulled off of studies, sanctioned, and even dismissed for conclusions that contradict the ideology of their bosses (43). This question does not concern who pays for what conclusions. It concerns a duty to act and to defend your own.

T R A G E D Y  O F  T H E  C O M M O N S ?

Web Resources
www.sciencemag.org/cgi/content/full/302/5652/1926/DC1

www.sciencemag.org
"Special Issue on the Tragedy of the Commons: VIEWPOINT: “Tales from a troubled marriage: Science and law in environmental policy” by O. Houck (12 Dec. 2003, p. 1926). It should have been noted in the Viewpoint that the text was based on Houck’s 2003 Robert C. Barnard Environmental Lecture, presented at the American Association for the Advancement of Science on 12 September.