PART I Introducing the Field

CHAPTER 1

Humanity and Technology

1.1 AN INTEGRATED SYSTEM

Whether we know it or not, whether we like it or not, technology strongly interacts with almost every facet of our lives. It has also come to interact with almost every facet of the natural world. It is this fundamental interdependence that creates the strong linkages between the studies of sustainable engineering, industrial ecology, and the more specific methodologies such as life cycle assessment that will be discussed throughout this book. Our discussion will frequently focus on the engineering or industrial aspects of particular projects or materials, but it should always be remembered that industrial ecology requires an awareness of the broader systems within which the projects or materials are embedded.

Furthermore, the integration of technology with social and environmental systems, a key aspect of sustainability, creates another important dynamic. Technology as a human competence is undergoing a rapid, unprecedented, and accelerating period of evolutionary growth, especially in the key foundational areas of nanotechnology, biotechnology, robotics, information and communications technology, and applied cognitive science. The implications for sustainability, and for industrial ecologists, are profound, and we will discuss them in more detail below. For now, it suffices to note that the effect is to undermine most of the assumptions underlying current engineering disciplines and policy frameworks. Indeed, industrial ecology itself is only beginning to fully engage with all the implications of technological evolution it purports to address.

1.2 THE TRAGEDY OF THE COMMONS

In 1968, Garrett Hardin of the University of California, Santa Barbara, published an article in *Science* magazine that has become more famous with each passing year. Hardin titled his article "The Tragedy of the Commons"; its principal argument was that a society that permitted perfect freedom of action in activities that adversely influenced common properties was eventually doomed to failure. Hardin cited as an example a community pasture area, used by any local herdsman who chooses to do so. Each herdsman, seeking to maximize his financial well-being, concludes independently that he should add animals to his herd. In doing so, he derives additional income from his larger herd but is only weakly influenced by the effects of overgrazing, at least in the short term. At some point, however, depending on the size and lushness of the common pasture and the increasing population of animals, the overgrazing destroys the pasture and disaster strikes all.

A more modern version of the tragedy of the commons has been discussed by Harvey Brooks of Harvard University. Brooks pointed out that the convenience, privacy, and safety of travel by private automobile encourages each individual to drive to work, school, or stores. At low levels of traffic density, this is a perfectly logical approach to the demands of modern life. At some critical density, however, the road network commons is incapable of dealing with the traffic, and the smallest disruption (a stalled vehicle, a delivery truck, a minor accident) dooms drivers to minutes or hours of idleness, the exact opposite of what they had in mind. Examples of frequent collapse of road network commons systems are now legendary in places such as Los Angeles, Tokyo, Naples, Bangkok, and Mexico City.

The common pasture and the common road network are examples of societal systems that are basically local in extent and can be addressed by local societal action if desired. In some cases, the same is true of portions of the *environmental* commons: improper trash disposal or soot emissions from a combustion process are basically local problems, for example. Perturbations to water and air do not follow this pattern, however. The hydrosphere and the atmosphere are examples not of a "local commons" but of a "global commons"—a system that can be altered by individuals the world over for their own gain, but, if abused, can injure all. Much of society's functions are embodied in industrial activity (where the word "industrial" should be interpreted broadly to mean any human action involving the transformation of materials or energy), and it is the relationships between industry, the environment, and society, especially the global commons, that are the topic of this book.

In the 40 years since Hardin's seminal paper, much additional effort has gone into generating a better conceptual picture of the use of what are now termed "common-pool resources." An example is provided by the fish stocks example of Figure 1.1. A feature of this example is that the linear relationship between fishing effort and cost contrasts sharply with the curvilinear relationship between fishing effort and revenue (i.e., number of fish caught). The yield (and the revenue) increases as fishing effort is increased until the maximum sustainable yield (MSY) is reached. After that point, increased effort draws down the stock of fish. However, the best return on effort (the maximum economic yield, MEY) occurs well before the maximum sustainable yield. As with the common pasture, if everyone fishes as an independent actor, neither the MEY nor the MSY is likely to be realized.

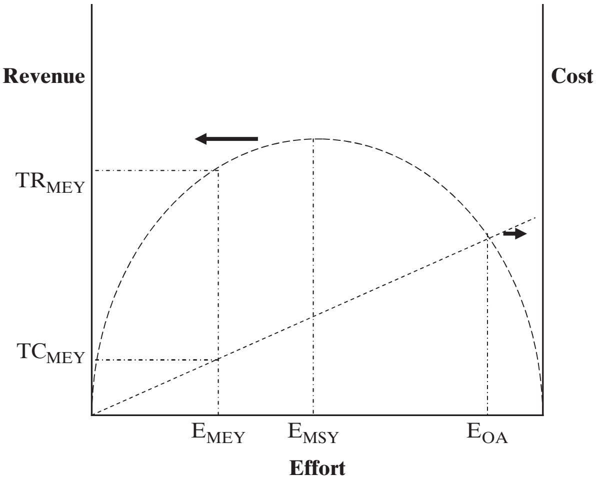


Figure 1.1

The relationships among fishing effort, cost, and revenue. The symbols are: TR: total revenue; TC: total cost; E: level of fishing effort; MEY: maximum economic yield; MSY: maximum sustainable yield; OA: open access. Adapted from R. Townsend, and J.E. Wilson, An economic view of the commons, in *The Question of the Commons*, B.J. McCay and J.M. Acheson, Eds., Tucson: University of Arizona Press, pp. 311–326, 1987.

Thus, the overuse of common-pool resources (as in the roadway example of Harvey Brooks) and the challenge of "free riders" who use a resource while doing nothing to sustain it create a need for institutions to oversee these resources. Municipal water authorities who meter water use are part of a common example of an overseeing institution. Institutions can also be established for the whole planet: The Montreal Protocol on Stratospheric Ozone Depletion demonstrates common-pool resource institutional functioning on the largest possible scale. Nonetheless, studies of a large variety of such institutions demonstrate that the success of common-pool institutions is generally related strongly to small geographical sizes, well-defined boundaries, shared cultural norms, and responsible monitoring and enforcement, that is, to systems where participants tend to know each other and where there is respect and trust in the institution overseeing the resource.

Environmentally related common-pool issues such as protection of coral reefs, land needed for ecosystem services such as hurricane protection, or emissions restrictions to protect the global atmosphere are often difficult institutional challenges. Climate change and resource depletion may often be only dimly visible, if at all, to individual actors. Scientific uncertainty complicates the process, as does the long timescale often existing between human action and impact.

Common-pool resources are of concern in industrial ecology and sustainable engineering because restricted availability of those resources could hamper progress due to modern technology. Conversely, thoughtless employment of technology could threaten the availability of energy, water, and the products of technology on which we depend—heating units, medical equipment, electronics, and so forth. The image of Hardin's cows on the village green can thus provide inspiration for a more intelligent technology, one based on minimal and careful resource use, high degrees of recyclability and reuse, and a perspective on life cycles—those of products, of infrastructure, and of colocated ecosystems. Because we have only one planet to work with, sustainability requires that technology work in harmony with the environment, not in opposition to it.

1.3 TECHNOLOGY AT WORK

It is undeniable that modern technology has provided enormous benefits to the world's peoples: a longer life span, increased mobility, decreased manual labor, and widespread literacy, to name a few. Nonetheless, there are growing concerns about the relationships between industrial activity and Earth's environment, nowhere better captured than in the pathbreaking report *Our Common Future*, produced by the World Commission on Environment and Development in 1987. The concerns raised in that report gather credence as we place some of the impacts in perspective. Since 1700, the volume of goods traded internationally has increased some 800 times. In the last 100 years, the world's industrial production has increased more than 100-fold. In the early 1900s, production of synthetic organic chemicals was minimal; today, it is over 225 billion pounds per year in the United States alone. Since 1900, the rate of global consumption of fossil fuel has increased by a factor of 50. What is important is not just the numbers themselves, but their magnitude and the relatively short historical time they represent.

Together with these obvious pressures on the Earth system, several underlying trends deserve attention. The first is the diminution of regional and global capacities to deal with anthropogenic emissions. For example, carbon dioxide production associated with human economic activity has grown dramatically, largely because of extremely rapid growth in energy consumption. This pattern is in keeping with the evolution of the human economy to a more complex state, the increasing growth in materials use and consumption, and an increased use of capital. The societal evolution has been accompanied by a shift in the form of energy consumed, which is increasingly electrical (secondary) as opposed to biomass or direct fossil fuel use (primary), the result being the now familiar exponential increase in atmospheric carbon dioxide that has occurred since the beginning of the industrial revolution. This trend is evidence that human activities are rapidly compromising the ability of the atmosphere to act as a sink for the by-products of our economic practices.

Human population growth is, of course, a major factor in this explosive industrial growth and expanded use and consumption of materials. Since 1700, human population has grown tenfold: It now exceeds six and one-half billion, and is anticipated to peak at nine billion or thereabouts in the twenty-first century. While this growth is generally recognized, it is less widely appreciated how human population growth patterns are tied to technological and cultural evolution. Indeed, the four great historical jumps in human population are synchronous with the initial development of tool use around 100,000 BCE, the agricultural revolution of about 10,000–3000 BCE, the industrial revolution of the eighteenth century, and the public health evolution that began in

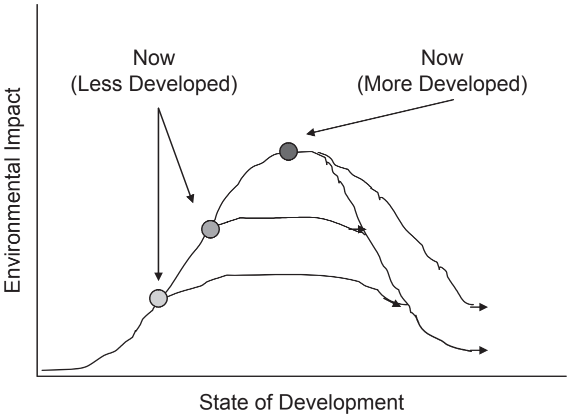


Figure 1.2

A schematic diagram of the typical life cycle of the relationship between the state of technological development of society and its resulting environmental impact.

about the mid-twentieth century. The industrial revolution actually consisted of both a technological revolution and a "neo-agricultural" revolution (the advent of modern agricultural practices), which created what appeared to be unlimited resources for population growth. Our current population levels, patterns of urbanization, economies, and cultures are now inextricably linked to how we use, process, dispose of, and recover or recycle natural and synthetic materials and energy, and the innumerable products made from them.

The above discussion suggests that the planet and its population are far from a steady state and may indeed be on an unsustainable path. Three illustrative routes toward long-term stability have been postulated: (1) managed growth until a long-term sustainable population/technology/cultural dynamic state (which we will call "carrying capacity") is achieved, (2) a managed reduction of population to a lower level sustainable with less technological activity, or (3) an unmanaged crash of one or more of the parameters (population, culture, technology) until stability at some undesirable low level is approached. Figure 1.2 suggests such possibilities. Note, however, that real trajectories will be much more complicated and dynamic; in particular, because population size, technology state, and culture are integrated and mutually dependent, as technology evolves, so might the potential carrying capacity of the planet.

This perspective has significant implications. When we objectively view the recent past—and 200 years is recent even in terms of human cultural evolution, and certainly in terms of our biological evolution—one fact becomes clear: The industrial revolution as we now know it is not sustainable over time. We cannot keep using materials and resources the way we do now, especially in the more developed countries. But what is the alternative?

1.4 THE MASTER EQUATION

A useful way to focus thinking on the most efficient response that society can make to environmental and related health and social stresses is to examine the predominant factors involved in generating those stresses. As is obvious, the stresses on many aspects of the Earth system are strongly influenced by the needs of the population that must be provided for and by the standard of living that population desires. One of the more famous expressions of these driving forces is provided by the “master equation”:

$$\text{Environmental Impact} = \text{Population} \times \frac{\text{GDP}}{\text{Person}} \times \frac{\text{Environmental impact}}{\text{Unit of GDP}} \tag{1.1}$$

where GDP is a country’s gross domestic product, a measure of industrial and economic activity. This equation has traditionally been called the IPAT Equation, where A = affluence (GDP/person) and T = technology (impact/unit of GDP). Let us examine the three terms in this equation and their probable change with time.

Earth’s population is, of course, increasing rapidly. For a specific geographical region (e.g., city, country, or continent), the rate of population change is given by

$$R = [R_b - R_d] + [R_i - R_e] \tag{1.2}$$

where the subscripts refer to birth, death, immigration, and emigration. Different factors can dominate the equation during periods of high birthrates, war, enhanced migration, plague, and the like. For the world as a whole, of course, $R_i = R_e = 0$. Given the rate of change, the population at a future time can be predicted by

$$P = P_0 e^{Rt} \tag{1.3}$$

where P_0 is the present population, t is the number of years in the projection, and R is expressed as a fraction. If R remains constant, the equation predicts an infinite population if one looks far enough into the future. Such a scenario is obviously impossible; at some point in the future, R will have to approach zero or go negative and the population growth will thus be adjusted accordingly.

In practice, demographers predict changes in R on the basis of the age structure of populations, cultural evolution, and other factors. Countries differ on these factors, of course, and the timing and magnitude of Earth’s eventual human population peak remain quite uncertain. Even in the mildest reasonable scenario, however, a global population much larger than the present level is anticipated.

The second term in Equation 1.1, the per capita GDP, varies substantially among different countries and regions, responding to the forces of local and global economic conditions, the stage of historical and technological development, governmental factors, weather, and so forth. The general trend, however, is positive, as seen in Table 1.1. This table reflects the aspirations of humans for a better life. Although GDP and quality of life may not be fully connected, we can expect GDP growth to continue, particularly in developing countries.

The third term in the master equation, environmental impact per unit of GDP, is an expression of the degree to which technology is available to permit development without serious environmental consequences and the degree to which that available technology is deployed. The typical pattern followed by nations participating in the industrial revolution of the eighteenth and nineteenth centuries is shown in Figure 1.2. The abscissa can be divided into three segments: the unconstrained industrial revolution, during which

TABLE 1.1 Growth of Real Per Capita Income in Developed and Developing Countries, 1960–2000

Country group	1960–1970	1970–1980	1980–1990	1990–2000
Developed countries	4.1	2.4	2.4	2.1
Sub-Saharan Africa	0.6	0.9	–0.9	0.3
East Asia	3.6	4.6	6.3	5.7
Latin America	2.5	3.1	–0.5	2.2
Eastern Europe	5.2	5.4	0.9	1.6
Developing countries	3.9	3.7	2.2	3.6

Note: The figures are average annual percentage changes, and for the "Developing countries" entry are weighted by population. Figures for 1990–2000 are estimated. (Data from The World Bank, *World Development Report 1992*, Oxford University Press, Oxford, UK, 1992.)

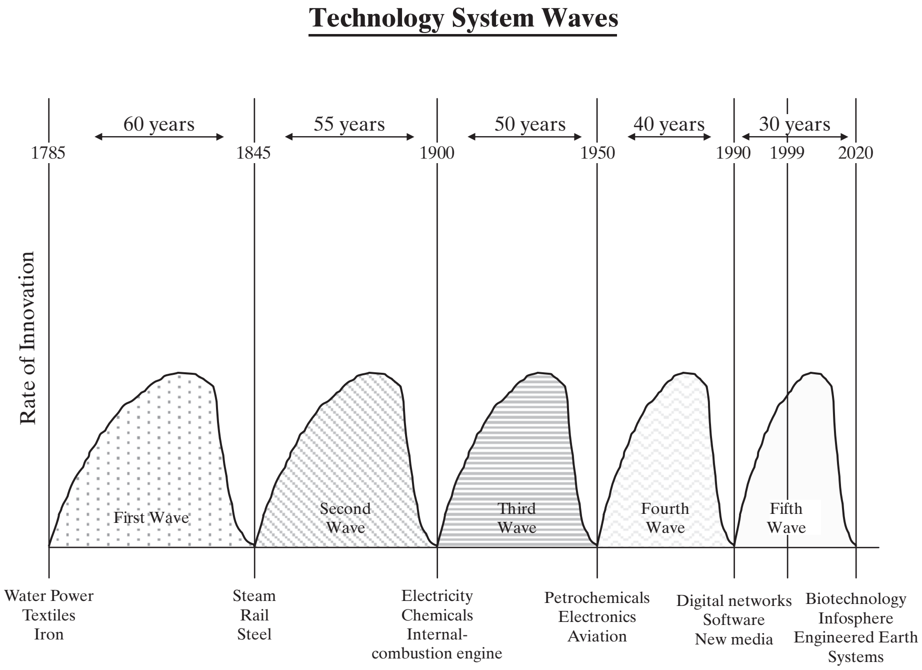
the levels of resource use and waste increased very rapidly; the period of immediate remedial action, in which the most egregious examples of excess were addressed; and the period of the longer-term vision (not yet fully implemented) in which one hopes that environmental impacts will be reduced to small or even negligible proportions while a reasonably high quality of life is maintained.

Although the master equation should be viewed as conceptual rather than mathematically rigorous, it can be used to suggest goals for technology and society. If our aim is to constrain the environmental impact of humanity to its present level (and one could make arguments that we need to do even better than that), we need to look at the probable trends in the three terms of the equation. The first, as discussed above, will likely increase by a factor of about 1.5 over the next half-century. The second is predicted to likely increase over the same time period by a factor of between two and three. Accordingly, to merely hold our environmental impact where it is today, the third term must decrease by something between 65 and 80 percent. This is the inspiration for calls for "Factor Four" or "Factor 10" reductions in environmental impact per unit of economic activity.

Of the trends for the three terms of the master equation, the one which perhaps has the greatest degree of support for its continuation is the second, the gradual improvement of the human standard of living, defined in the broadest of terms. The first term, population growth, is not primarily a technological issue but a social issue. Although countries and cultures approach the issue differently, the upward trend is clearly strong. The third term, the amount of environmental impact per unit of output, is primarily a technological term, though societal and economic issues provide strong constraints to changing it rapidly and dramatically. It is this third term in the equation that appears to offer the greatest hope for a transition to sustainable development, especially in the short term, and it is modifying this term that is among the central tenets of industrial ecology and sustainable engineering.

1.5 TECHNOLOGICAL EVOLUTION

Technological evolution generally proceeds in one of two ways. Most of the time, technological evolution is incremental, marked by small improvements or changes in existing products or systems that, taken together, improve the quality of life but do not significantly change economic, cultural, or natural systems. In some periods, however, so-called "transformative technologies" change the technological landscape so profoundly that change in the related systems is significant and often difficult. Indeed, economists have identified stages in economic development that can be associated with particular enabling technologies (Figure 1.3). For example, the introduction of the railroad, the automobile, and electricity changed not just economic and related technological systems, but also culture, national competitiveness, political systems, and most people's way of life at the individual level. It is indeed accurate to say that the railroad was a necessary, and enabling, technology for the rise of Britain as a world economic and political power. It also necessitated other technologies, such as national communications systems using Morse Code, and required accurate



Based on Joseph Schumpeter and Nikolai Kondratieff

Figure 1.3

Economists have identified a relationship between enabling technologies and patterns of economic growth. This relationship hints at the changes in employment, family and personal life, and cultural systems which such technologies frequently entail (consider the effect of the automobile on society, for example). Given this historical view, it is possible to anticipate significant changes as several enabling technologies—nanotechnology, biotechnology, ICT, robotics, and cognitive science—achieve critical mass together, but not to predict with any certainty specific outcomes of that process. Note also that the rate of substitution of enabling technologies has itself accelerated, suggesting an auto-catalytic effect: the more technology humans have, the more rapidly they build on that to create more. Based on Joseph Schumpeter and Nikolai Kondratieff.

timekeeping, thus changing the way time was perceived and measured around the world. Among the other effects of extensive railroad infrastructure was helping to make the American Midwest a viable agricultural enterprise, feeding products to the American East Coast and from there to global markets (and leading to the development of Chicago in the process). That a single technology so structured vast areas of land and affected the economic well-being and personal lives of so many helps make clear the relationship between sustainability and technology.

Given this example, what are we to make of the confluence and accelerating evolution of an entire suite of foundational technologies: nanotechnology, biotechnology, information and communications technologies (ICT), robotics, and cognitive science (sometimes termed the "NBIRC" technologies)? Each by itself has profound implications; taken together, they pose a daunting challenge in at least several ways. First, as they evolve, they greatly increase the complexity of the systems with which industrial ecology deals. This is illustrated by, for example, the integration of enhanced ICT capabilities in urban systems, as discussed in Box 1.1.

Urban Systems: An Industrial Ecology Focus

Perhaps the most obvious demographic trend in modern societies around the world is urbanization. Demographers estimate that about 80 million people a year are moving into cities. Looking forward, the United Nations estimates that the urban populations of Africa, Latin America, and Asia will double over the next 30 years, growing from 1.9 billion in 2000 to 3.9 billion in 2030. By that time, over 60 percent of the world's population will live in cities. Moreover, cities are critical to the social side of sustainability, because they are usually the economic and cultural centers of their regions and have significant roles as consolidation points for energy, water, and material flows. Nonetheless, cities are not well understood at the systems level, an especially worrisome gap given the importance of urbanization as a fundamental demographic trend, the concerns regarding fragility of urban systems in case of natural disaster or deliberate attack, the complexity of the interactions among different infrastructures, and urban systems and their environmental contexts.

Given their central role in human society, urban systems will be significantly affected by a number of technological trends. For example, should people in developed countries routinely begin living past 100, the implications for design of urban buildings, infrastructure, and transportation networks will be significant. But a more challenging example arises when two separate trends, one in urban system design and the other in ICT, are considered together. The nature of urban systems is changing profoundly as ICT capability is increasingly integrated into all levels of urban functionality: smart materials, smart buildings, smart infrastructures, and the like. Sensor systems, sometimes coupled to computers and control devices, are becoming increasingly common. Cities are becoming much more information intensive at all levels. At the same time, ICT systems are changing fundamentally: being

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redesigned to be what engineers call "autonomic"—that is, virtualized—and made self-defining, self-monitoring, self-healing, and learning-capable. Moreover, the concomitant introduction of grid computing networks and wireless communications at scales from local to regional to global, combined with the increasing role of urban systems as nodes in energy and financial networks, adds many layers of information complexity to built urban environments.

The implications of these trends for urban systems design, performance, and behavior are not well understood. Some idea of the possibilities and the need for concern can be obtained, however, from the experience of Black Monday, October 19, 1987. The Dow Jones Industrial Average fell 22.6 percent on that day, even though there were no significant changes in underlying financial conditions that warranted such a collapse. Rather, many analysts attributed the occurrence to systems dynamics. What had happened was that many stock trading firms had begun to computerize their trading activity, including building "floors" into their pricing models. Thus, when a certain fall in the market had occurred, the computers, which were not electronically or operationally coupled together, were instructed to sell to minimize losses. When the market declined beyond a certain point, increasingly sophisticated computerized program trading systems began selling into a declining market, creating an unforeseen negative feedback loop that emerged not from individual machines, but from the behavior of the market as a whole. The result was a market crash. Given that these trading systems were far, far simpler than the autonomic structures now being integrated into urban systems in all sorts of formal and informal ways, the potential systems dynamics of urban ICT systems cannot be assumed to be benign.

Second, such rapid (and accelerating) technological evolution undermines and makes contingent many societal assumptions which, because they have changed relatively slowly in the past, are generally assumed to be stable. An obvious example is the span of human life. Many governmental approaches assume that the existing life spans, which vary between 70 and 80 years for many developed countries, are essentially stable through time. But many who work in the medical field believe that within a few decades the expected life span of an individual born in a developed country will be well over 100 years. Under such a scenario, demand and consumption patterns would shift significantly. And this is only one, relatively foreseeable and trivial, implication of the integrated technological evolution that is inevitable at this point.

Technological evolution is thus a major part of the context within which sustainable engineering and industrial ecology studies are conducted. At smaller scales, it may be adequate to simply explicate and revalidate assumptions about technology that underlie the methodology and particular project. At larger scales, however, technological change in itself must be part of industrial ecology studies; indeed, the transdisciplinary nature of industrial ecology is a critical framework for such studies.

1.6 ADDRESSING THE CHALLENGE

The twentieth century was a period of enormous progress, achieved in part by ignoring the possible consequences of the ways in which that progress was being made to happen. The conjunction of inadequately thought-out technological approaches with rapidly rising populations and an increasing culture of consumption is now producing stresses obvious to all.

There are roles for many players in addressing the need to transform the technology–society–environment relationship. Social scientists need to understand consumption and how it may evolve and be modified. Environmental scientists and material specialists need to understand the limits imposed by a planet with limited resources and limited assimilative capacity for industrial emissions. Technologists need to develop design and manufacturing approaches that are more environmentally sound. Industrialists need to understand all these frameworks for action and develop ways to integrate the concepts within today's corporate structures. Policy makers need to provide the proper mix of regulations and incentives to promote the long-term health of the planet rather than short-term fixes.

These are great challenges. They are the ones to which this book is addressed. We cannot treat all of them in detail, nor are all of them sufficiently developed to permit doing so even if we wished. Nonetheless, we can see many approaches that will take us in the right direction. It is time to get started.

FURTHER READING

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EXERCISES

1.1 In 1983, the birthrate in Ireland was 19.0 per 1000 population per year and the death rate, immigration rate, and emigration rate (same units) were 9.3, 2.7, and 11.5, respectively. Compute the overall rate of population change.

1.2 If the rate of population change for Ireland were to be stable from 1990 to 2005 at the rate computed in the above problem, compute the 2020 population. (The 1990 population was 3.72 million.)

1.3 Using the "master equation," the "Units of Measurement" section in Appendix, and the following data, compute the 2007 GDP/capita and equivalent CO_2 emissions per equivalent U.S. dollar of GDP for each country shown in the following table.

2007 Master Equation Data for Five Countries

Country	Population (millions)	GDP (billion of U.S. dollars)	CO_2 emissions (Tg C/yr)
Brazil	188	621	106
China	1,314	2,512	1,665
India	1,095	796	338
Nigeria	132	83	114
United States	298	13,220	1,709

Source: Data for this table were drawn primarily from J.T. Houghton, B.A. Callander, and S.K. Varney, *Climate Change 1992*, Cambridge, UK: Cambridge University Press, 1992.

1.4 Trends in population, GNP, and technology are estimated periodically by many institutions. Using the typical trend predictions below, compute the equivalent CO_2 anticipated for the years 2010 and 2025 for the five countries in the following table. Graph the answers, together with information from 2007 (previous problem), on an ECO_2 vs. year plot. Comment on the results.

Master Equation–Predicted Data for Five Countries

	Population (millions)		GNP growth (%/yr)		Decrease in
Country	2000	2025	1990–2000	2000–2025	ECO_2/GNP(%/yr)
Brazil	175	240	3.6	2.8	0.5
China	1,290	1,600	5.5	4.0	1.0
India	990	1,425	4.7	3.7	0.2
Nigeria	148	250	3.2	2.4	0.1
United States	270	307	2.4	1.7	0.7

Source: Data for this table were drawn primarily from J.T. Houghton, B.A. Callander, and S.K. Varney, *Climate Change 1992*, Cambridge, UK: Cambridge University Press, 1992.