ELSEVIER

Ecological Economics 30 (1999) 267–284

ECOLOGICAL ECONOMICS

www.elsevier.com/locate/ecolecon

ANALYSIS

Knowledge and the environment

Paul R. Ehrlich [a,*], Gary Wolff [a], Gretchen C. Daily [a], Jennifer B. Hughes [a], Scott Daily [a], Michael Dalton [a,b], Lawrence Goulder [c]

[a] *Center for Conservation Biology, Department of Biological Sciences, Stanford University, Stanford CA 94305, USA*
[b] *Institute for International Studies, Stanford University, Stanford CA 94305, USA*
[c] *Department of Economics, Stanford University, Stanford CA 94305, USA*

Received 11 June 1998; received in revised form 9 November 1998; accepted 11 November 1998

Abstract

Some recent analyses suggest that future increases in knowledge will, more or less automatically, alleviate or even eliminate future environmental problems. Here we examine this issue. First, we discuss whether a knowledge explosion is indeed occurring, addressing some of the problems with assessing knowledge-growth. We next consider whether growth in knowledge will help the environment; we ask whether future advances in knowledge are likely to assure benign environmental outcomes, and discuss physical limitations of reducing resource consumption. Finally, we outline policy interventions that would help produce and implement environmentally helpful knowledge. Although knowledge-growth can help attenuate future environmental problems, we are skeptical as to the ability of advances in knowledge to offset fully the adverse environmental impacts of continued growth of population and per-capita consumption. The ongoing shift from a material-based to a services-based economy reduces, but does not eliminate, the significant environmental impacts associated with the increasing scale of economic output. In addition, the ability of the economy to replace certain key natural resource inputs with knowledge inputs must eventually encounter limits. Public policy has a crucial role both in discouraging environmentally damaging forms of consumption, and in promoting the generation and diffusion of environmentally beneficial knowledge. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Environment; 1 = PAT; Service economy; Essential resources; Knowledge

1. Introduction

There is no question that increased knowledge must play an essential role in solving humanity's environmental problems. Knowledge can help limit and reduce population size (Ehrlich and Holdren, 1971; Ehrlich and Ehrlich, 1990), change patterns of overconsumption (Ehrlich et al., 1997), and develop more environmentally benign technologies (World Commission on Environment and Development, 1987; Holdren, 1990; Kane,

* Corresponding author.

0921-8009/99/$ - see front matter © 1999 Elsevier Science B.V. All rights reserved.
PII: S0921-8009(98)00130-X

1996). These connections between knowledge and the environment are relatively uncontroversial. Some recent analyses suggest, however, that knowledge-growth may alleviate environmental problems in a way that is largely unprecedented. Although history provides numerous examples where industrialization has produced unfortunate environmental consequences, some argue that knowledge-growth will assure high levels of environmental quality in the future. According to this view, the continued discovery of cleaner, low-pollution production methods will preserve environmental quality, despite increases in the scale of global output and consumption.

A related, but distinct view is that we no longer need to worry about the possibility that the finiteness of natural resources will pose a drag on future economic growth. In this connection, there have been repeated discussions of an economic transition to a services-, or knowledge-, economy (Porat, 1977; Drucker, 1993; Chichilnisky, 1996; Chichilnisky, 1998). Chichilnisky (1998) proposed that a knowledge revolution is underway that will allow more economic output with less physical input. It is "a social and economic revolution which matches the impact of the agricultural and industrial revolutions," one in which land and machines as factors in production are being replaced by knowledge. An extreme version of this claim is that future growth in technology will virtually eliminate the possibility of a resource drag on the economy. The thrust of this argument can be seen in the following (Sagoff, 1997): "It is simply wrong to believe that nature sets physical limits to economic growth—that is, to prosperity and the production and consumption of goods and services on which it is based. (p. 83) … Although raw materials will always be necessary, knowledge has become the essential factor in the production of goods and services (p. 90)."

Here we examine the question whether knowledge-growth will, in some sense, save the environment. We first discuss whether a knowledge explosion is in fact occurring, pointing out along the way some basic challenges involved in assessing an increase in knowledge. Second, we address the question: if knowledge is growing, will it help the environment? Here we consider both the issue of whether knowledge can avoid a resource drag, and the question whether knowledge can overcome the threats to the environment implied by increasing global output and consumption. Finally, we outline policy interventions that would help society overcome barriers to producing and acting upon environmentally helpful knowledge. As our discussion will make clear, the productive use of knowledge—to serve environmental or other purposes—requires more than just knowledge-acquisition or discovery. The acquired knowledge must be put to good use. Appropriate institutions, such as new financial institutions to securitize[1] the biosphere, have a vital role in meeting this challenge. Likewise, public policies, such as subsidies to research and development, are crucial for providing adequate incentives for the creation of knowledge and for countering forces of disinformation.

2. Is a knowledge explosion occurring?

In assessing whether knowledge-growth is occurring, the first step is to define knowledge. We define knowledge as accurate information that has been organized and evaluated by a human mind (or minds) and that has shaped actions, beliefs, attitudes, institutions or mental states (e.g. sense of well-being). Under this definition, information does not become knowledge until it is organized in a way that makes it useful. We include the qualifier "accurate" in our definition in keeping with the idea that disinformation does not constitute knowledge. Our definition may not be completely satisfactory, but it seems to serve our purposes well.

Our definition of knowledge roughly corresponds to what economists typically call the level of technology. Economists usually identify technology with know-how or the current stock of knowledge. Likewise, economists define technological change as an increase in the stock of knowledge. Although our definition of knowledge is consistent with economists' use of the concept,

[1] Securitization involves issuing tradable securities that entitle investors to a share of the benefits from a venture.

our application of the concept is broader than the usual economic application. Economists generally apply the concept of knowledge to the technologies embodied in production methods or processes. In the present paper, we consider the knowledge embodied in social decisions as well, including the knowledge of which public policies are useful (and which are not) and of what kinds of institutions can be effective in serving social needs. In other words, we stress the importance of knowledge to public policies and to institutions, as well as to private business decisions.

Beyond the difficulties of defining knowledge, there is the problem of measuring it. This problem is central to determining the relative importance of new knowledge. Journalist John Horgan, in his book *The End of Science* (Horgan, 1996), has claimed that the rate of important discoveries in science is declining, despite the mounting flood of information. In light of the differences between information and knowledge, it might well be claimed that the recent development of computers has been overrated, and that the impact of computers on the environment (and society) is still dwarfed by earlier, more fundamental discoveries, such as writing, accounting, the printing press, telegraph, telephone, xerography, radio, and television. Without the first three there would have been no industrial revolution, and the last four have utterly changed the way people gain and distribute knowledge.

It is true, however, that recent advances in information technology are enormous. These advances not only have allowed the gathering of masses of information, but also have made it easier than ever to share work in progress. Thus, perhaps much of the appearance of an information explosion is actually the dissemination or transmission of knowledge that previously was not broadly shared. Also, the number of scientists has increased, so the total amount of knowledge being shared is naturally rising for this reason as well.

As our definition of knowledge indicates, only useful and accurate information counts as knowledge. In the environmental area, much of the information that is purveyed as useful is actually disinformation, information that is intended to deceive (Ehrlich and Ehrlich, 1996). In judging the extent to which knowledge-growth is occurring, we should in some sense subtract the disinformation from the useful information, as well as adjust for quality differences, since disinformation and low quality information obviously impede improved policy responses to all kinds of problems, including environmental ones. But so far there has been no systematic evaluation of how the problem of disinformation should be dealt with. Any policy-relevant method would need to sidestep the contentious issue of trying to determine what is or is not disinformation (think about advertising) and concentrate instead on installing disincentives to its fabrication.

A final issue in measuring knowledge-growth is the need to acknowledge lost potential knowledge. Such losses are associated, for example, with the decay of biodiversity and cultural diversity. Are the gross increases in knowledge enough to compensate for the lost potential knowledge embedded in the biological and cultural diversity that we are losing?[2] Perhaps we are being inundated by a flood of trivial knowledge while incurring a net loss of more fundamental knowledge.

At the core of claims for a knowledge revolution is the assertion that our knowledge base and economy have changed significantly in recent years. In some respects this is clearly true. To take just one example of knowledge growth, the ever-increasing processing power of computers (doubling approximately every 18 months) has improved our understanding of climatology and hydrology through more powerful modeling capabilities. Looking at the economy, the US is increasingly a service-based economy. Employment doubled in the services sector from 1970–1995 and services now account for over 75% of GNP

[2] One can think of the genetic code as a carrier of information which is processed into organisms whose morphologies, behaviors, and evolutionary histories could be considered to amount to potential knowledge—certainly at a higher level than unexamined data from satellite sensors, for example. The loss of knowledge embedded in cultural diversity (including languages), and of non-industrial human knowledge such as that of the medicinal uses of plants, is very closely related. Should these be considered in evaluating the net changes in knowledge?

and up to 80% of total employment (Guile and Cohon, 1997; Rejeski, 1997). A number of these growth service industries, such as finance and telecommunications, are knowledge-based. At the moment, however, we will remain agnostic about whether there have been sufficient fundamental changes in humanity's stock and use of knowledge to constitute a revolution, and simply examine the relationship of knowledge to environmental quality and ways to make that relationship more positive.

3. Will more knowledge help the environment?

3.1. Knowledge, the environment, and the $I = PAT$ equation

Although it seems to us that, even after accounting for disinformation and knowledge-losses, the overall stock of knowledge probably is growing, it is a separate question whether knowledge will lead to a more environmentally sustainable civilization. The thesis that the knowledge revolution will solve the environmental part of the human predicament can be cast in terms of the $I = PAT$ equation (Ehrlich and Holdren, 1971; Ehrlich and Ehrlich, 1990), which states that damage to the environment (impact, such as land degradation or loss of biodiversity) is a product of population size (P), per capita affluence (A) measured as per capita consumption, and the environmental impact of the technologies, cultural practices, and institutions through which that consumption is serviced (T), measured as damage per unit of consumption. Saying that knowledge will help the environment is tantamount to saying that reductions in the T factor stemming from knowledge-growth will significantly offset the environmental damages associated with increases in the P and/or A factors. There are several reasons why knowledge-growth might not lead to this outcome.

First, some knowledge is not relevant to the quality of the environment. Knowledge of marketing psychology is largely environmentally irrelevant, while knowledge about the carbon dioxide content of the atmosphere and its significance is very consequential.

Second, although changes in T are likely to provide some compensation in particular instances, the net environmental effect of a rapid growth in knowledge is not inevitably positive—in some cases, T effectively rises, rather than falls. Some knowledge will be used to develop or improve technologies that may have a negative impact on environmental quality. For instance, a strong case can be made that the agricultural and industrial revolutions traded off certain aspects of environmental quality for improvements in the quality of human life in many other dimensions—at least for a substantial portion of humanity. We do not contend that the net effect of these revolutions was negative, although one might make that argument.[3] We only point out that many aspects of environmental quality have certainly declined as a result of these revolutions (Ehrlich et al., 1977; Ehrlich and Ehrlich, 1990; Ehrlich et al., 1995). In fact, there is every sign that growth of critical environmental problems such as the loss of biodiversity (Myers, 1979; Ehrlich and Ehrlich, 1981; Wilson, 1992; Ehrlich, 1995), land degradation (Daily, 1995), climatic alteration (Schneider, 1989; Intergovernmental Panel on Climate Change, 1996; Schneider, 1997), and toxification of the biosphere (Colborn et al., 1996) have been strongly positively correlated with the growth of knowledge. Consequently, if a knowledge revolution is to be good for the environment, it must have an entirely different relationship with the environment than the agricultural and industrial revolutions.

Third, even if T tends to fall through time, there is no guarantee that this will fully offset the changes in P and A. And finally, one cannot count on significant reductions in T continuing for the very long term. All production of economic goods and services—even if it involves nothing more than manipulation of information—requires the use of energy. And no means of providing energy is or can be free of resource consumption and environmental impact (although, of course, some means are better than

[3] There have been claims that hunter-gatherers lived quite high-quality lives (Sahlins, 1972). This remains a difficult issue to evaluate, as are most quality-of-life issues.

others). There are ultimate (thermodynamic) as well as practical (economic) limits to how much the energy use connected with a given service can be reduced, and to how much the raw resource use and environmental impact of providing this energy can be reduced. Thus the T factor cannot be made arbitrarily small to compensate for the product of P and A becoming arbitrarily large.

3.2. Knowledge growth, sectoral shifts, and the use of material inputs

One empirically testable claim for a positive relationship between increasing knowledge and environmental quality is that knowledge is replacing some elements of natural and human-made capital, such as land and machines, as factors of production. This proposition suggests that the advance of knowledge will reduce pressures to utilize natural capital and thereby avoid the adverse environmental consequences associated with the loss of such capital. Knowledge is now recognized as a primary factor of production. Economic growth models that explicitly account for growth of knowledge better explain growth in national aggregate output than those that do not. Paul Romer (Romer, 1986; Romer, 1990) has shown that more-developed economies may grow faster than less-developed economies because the former rely more on knowledge as a factor of production. Economies that rely more heavily on knowledge are able to grow faster, Romer argues, because of knowledge spillovers. An example of such spillovers is provided by the development of video-recorder technology by the Sony Corporation. Although Sony developed and patented this technology in the form of Betamax, the company could not hide the fact that video-recorders were now possible and marketable. Nor could they prevent engineers from leaving the company to work for competitors. Ultimately, they lost the market to VHS. This example illustrates that knowledge can be transferred from one firm to another at relatively low cost. Although Sony may lament this attribute of knowledge, the phenomenon of low-cost spillovers is potentially beneficial to society as a whole (so long as the prospect of spillovers does not stifle incentives to innovate, as discussed below). Thus, as knowledge becomes a more important input into production, the spillover phenomenon gains significance, and helps lower the economy-wide costs of production. Economies in which knowledge plays a lesser role benefit less from low-cost knowledge dissemination, and stay behind or fall further behind (become less competitive in knowledge-intensive goods production). Similarly, Mankiw et al. (1992) demonstrated that cross-country patterns of growth are explained better when human capital (worker education and skill level) is included in the analysis.

Even if knowledge is becoming a more important factor of production in more-developed economies, and even if this allows more-developed economies to achieve a higher rate of economic growth, this is not automatically good news for the environment. After all, economic growth is not always accompanied by an increase in environmental quality—especially under conventional definitions of economic growth. Thus it is necessary to examine closely the connection between knowledge as a production input and environmental quality. Some have argued that the increased reliance on knowledge as a factor of production coincides with the shift in emphasis from the manufacturing sector to the services sector. Even if the services sector continues to grow more rapidly than manufacturing, this does not necessarily imply a decrease in total quantities of physical resources mobilized or a decrease in environmental impacts.

With historical data we can observe the connections between sectoral shifts and the use of materials inputs. Although our ultimate concern is environmental quality, we focus on materials inputs on the assumption that it correlates with environmental damage. In many instances the correlation is quite strong: global warming is a function of total emissions of greenhouse gases, and loss of habitat for biodiversity is a function of total area of natural ecosystems converted to human purposes.

Recent data show trends toward lower resource use per unit of gross domestic product (GDP). Fig. 1 illustrates the total material used by each of four nations (the US, Germany, the Netherlands,

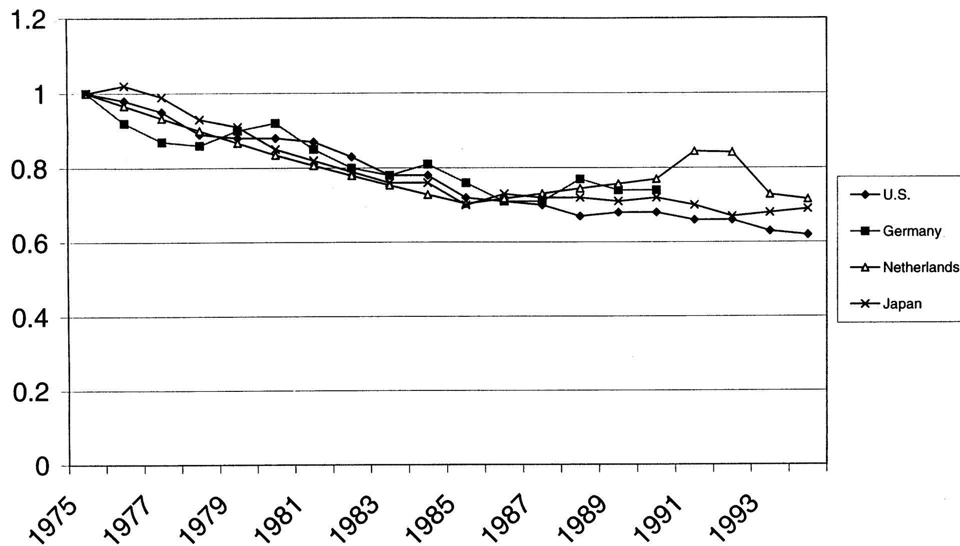

Fig. 1. Material used per unit GDP relative to 1975 for four countries.

and Japan) per unit of GDP from 1975 through 1994 (World Resources Institute, 1997). Because GDP is denominated in the currency of each nation, the data have been normalized to an arbitrary reference value of 1.0 in 1975. Although the methodology was necessarily crude in some respects, it does attempt to account for the materials used in production of imports, so migration of heavy industries to less industrialized countries should not bias the data.

The downward slope in all four countries suggests that physical inputs are becoming less important per unit of economic output. This pattern reflects the contributions of two factors: an increase in knowledge that reduces the need for materials inputs in given industries (the T in the $I = PAT$ equation), and a shift away from relatively materials-intensive manufacturing toward less materials-intensive service industries. Thus, both changes in the nature of production as well as changes in the composition of the economies' output have contributed toward the reduction in the use of materials inputs per unit of economic output.

These trends offer some consolation for those interested in environmental protection. But they do not provide the whole story. Other factors can offset these positive trends. In particular, rising affluence partially or completely offsets the shifts toward services and knowledge-intensive production. Fig. 2 shows the total (relative) mass of materials per capita used in each nation from 1975 through 1994. Because income has grown in these nations, metric tons per capita have not fallen as much as tons per unit of GDP. In fact, tons of resources consumed per capita have been rising in Germany, Japan and the Netherlands. Thus, accounting for rising incomes (A) demonstrates that the environmental benefits of the impressive downward slope in Fig. 1 are offset in three of the four countries examined.

Population growth is also countering the trend toward a less materials-intensive society. Fig. 3 illustrates the total (relative) quantity of materials used by each nation from 1975 through 1994. It demonstrates why A and P are as important as T in the $I = PAT$ equation. Those who believe that historical progress in T (a partial surrogate for knowledge) will automatically solve environmental problems have not examined the whole picture. Taking both P and A into account shows that reductions in T are offset in all four of the nations. Moreover, these nations are developed countries; in most developing countries, population is increasing and the shift toward services and knowledge-based production is not as strong.

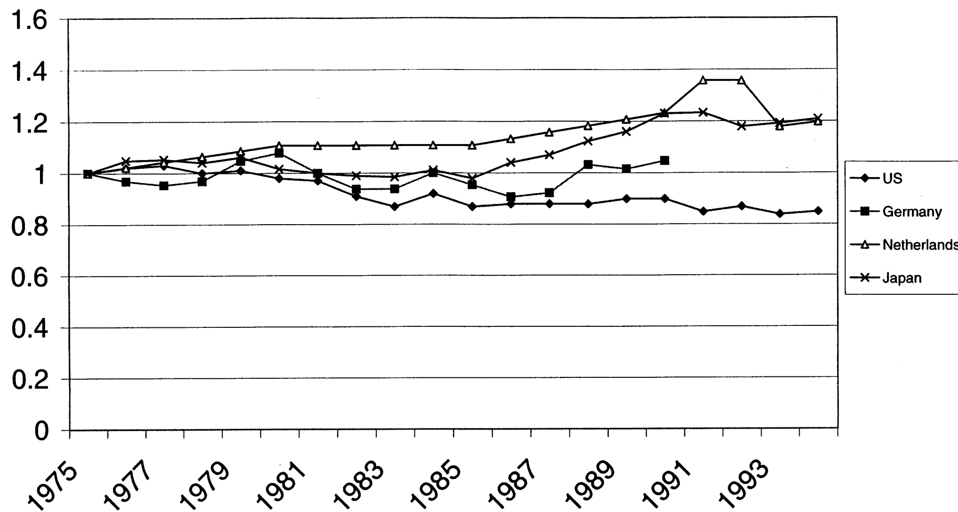

Fig. 2. Material used per capita relative to 1975 for four countries.

Thus, we suspect that despite improvements in *T*, global *I* has probably not declined.

3.3. Some complications

There are a number of further issues that complicate the relationship between knowledge-growth and the environment. One is that reducing *T* is likely to become increasingly difficult since, as *P* and *A* grow, materials will be extracted from scarcer and/or less concentrated non-renewable stocks, from less productive renewable sources, and from more remote areas (Ehrlich and Holdren, 1971; Ehrlich and Ehrlich, 1991; p. 7). Second, knowledge-growth itself contributes to overuse of some renewable resources. Even with the shift towards a computerized office, paper consumption has increased in absolute terms over time and has actually held steady on a per GDP basis (Stern et al., 1997). As another example, advances in the associated development of more advanced fishing and logging methods have made overharvesting of stocks relatively easy (Safina, 1997; Pauly et al., 1998).

Third, if knowledge-growth is to help the environment, it needs to do more than reduce our reliance on inputs of natural capital. To be sure, reducing this reliance is vitally important—to a large extent, knowledge growth must overcome the input scarcity problem by revealing ways that economic output can be produced with less reliance on increasingly scarce inputs. There is another, equally important part of the environmental problem, however. A major reason for environmental degradation is the discharge of contaminants associated with economic production. This discharge problem is evident in local and regional air and water pollution as well as more global environmental problems such as stratospheric ozone depletion, transboundary acid deposition, and global climate change. To deal with the discharge problem, there is a need for knowledge of new production methods that reduce emissions of toxic chemicals and other contaminants to the Earth and its inhabitants. To the extent that economies reduce their dependence on fossil-based energy, they alleviate both the input scarcity problem (by reducing reliance on non-renewable resources) and the discharge problem (by reducing emissions associated with the combustion of fossil fuels).

But many serious environmental problems result from discharges that are not strictly energy-related. For instance, synthetic chemicals can have damaging effects in humans and other animals (Colborn et al., 1996) even though the quantities of resources used in the production of those chemicals is quite small. Certainly, knowledge can

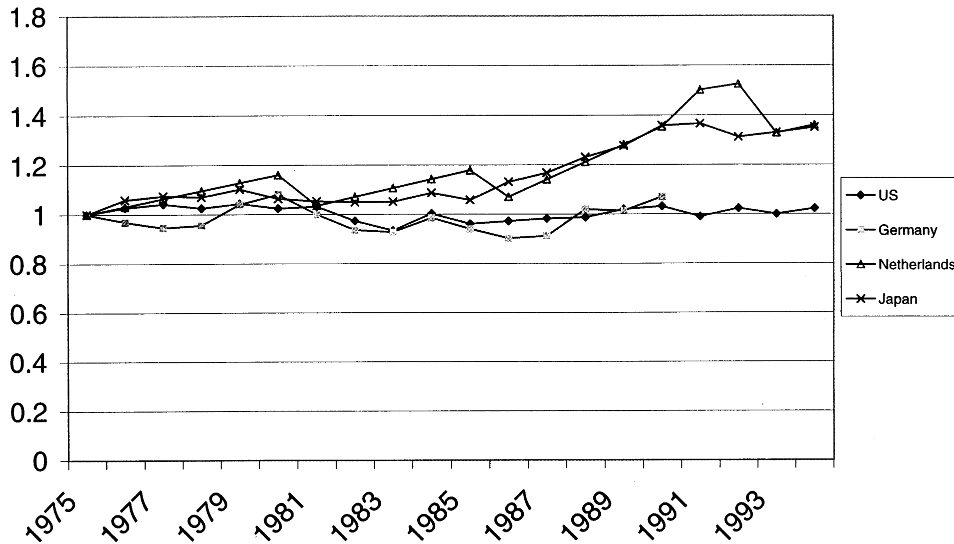

Fig. 3. Total quantity of materials used relative to 1975 for four countries.

be instrumental in controlling pollution by these chemicals, but the synthesis of new organic compounds with unknown biological impacts proceeds apace. At least in developed countries, net gains in pollution control may be occurring, although even this trend is difficult to assess; simple measures of decreases in pollutants that lower air or water quality often do not tell the whole story.[4]

In addition, since environmental damages often stem from terrestrial and atmospheric concentrations (stocks) of toxic compounds, rather than current emissions (flows) of these compounds, merely reducing the flow will not immediately lead to significant environmental improvement. This issue is particularly important in the context of stratospheric ozone depletion or global climate change—problems that depend on atmospheric concentrations of CFC's, carbon dioxide, and other greenhouse gases.

3.4. Essential resources and the limitations of knowledge growth

Perhaps the most difficult challenges for continued economic growth are posed by essential resources—these are resources that are crucial for economic production and for which there are no conceivable substitutes in production.[5] Stocks of renewable and nonrenewable natural resources are finite in supply—their supply is largely given by nature, rather than augmented by human beings. As population grows and labor inputs as well as reproducible capital stocks expand, the

[4] For instance, wastewater treatment plants often dispose of their sludge in landfills that in turn send leachate collected in their underdrain systems to wastewater treatment plants, or tall smokestacks convert local air quality problems into regional acid precipitation problems. A recent example is the use of methyl tertiary butyl ether (MTBE) as a gasoline oxygenate (additive) which reduces automobile emissions of carbon monoxide and volatile organic compounds. MTBE is considered one of the best oxygenates for this purpose. MTBE, however, is extremely mobile in groundwater—a fact apparently not examined when it was selected for use as an air pollution control technique. California is currently considering banning its use as a gasoline additive because of the costly groundwater contamination problems that have resulted from its use in air pollution control.

[5] Economists define whether an input (e.g. natural capital, manufactured capital, and labor) is essential in terms of an aggregate production function. An input is defined as essential if the amount of aggregate production (the value of this function) approaches zero in the limit as the quantity of the input approaches zero. This means that if certain types of natural capital are essential, then the depletion of the stocks of these types of capital implies a *reduction* in economic output and consumption in the long run.

stocks of productive natural resource inputs become relatively scarce in comparison with other productive inputs. If these natural resources are essential, their increasing relative scarcity will constrain economic growth and constitute the most extreme kind of input scarcity. Thus it seems important to consider the extent to which natural resources are indeed essential. Can future human needs be satisfied despite the finiteness of these resources? Can reasonable levels of consumption be maintained even when essential resources are fixed (or, in the case of exhaustible resources, shrinking) in supply? Can advances in knowledge somehow offset the increased relative scarcity of essential natural capital?

Even after implementing the most environmentally friendly technologies, some minimal level of consumption of physical resources would be required. After all, people can't eat or drink services, information, or knowledge any more than a group of chimpanzees grooming one another could survive on that exchange of services alone.[6] If these physical resources are not being used sustainably—that is, without reducing the ability of the planet to supply these resources in the future—then humanity is having a negative impact on the environment.

In some cases, new knowledge can convert an input from the category of essential to that of inessential. However, there are some inputs or resources for which no amount of knowledge is likely to alter the essentiality. Here we focus on resources that are likely to remain essential, despite advances in knowledge. The key questions we will ask are: (1) which material resources are essential?; (2) of these, which are currently (or projected to soon be) scarce?; (3) to what extent could increased knowledge increase access to, or reduce the per-capita amount required of, these resources?; and (4) is the rate of innovation sufficiently rapid to offset increases in their consumption driven by increases in population size and per-capita affluence?

Naming essential resources is easy for ecologists. After all, a central theme in ecology is what resources limit the distribution and abundance of organisms. Water, fertile soils, energy, and biodiversity are examples of resources essential to humanity (Daily and Ehrlich, 1992). Note that all are intimately involved in maintaining humanity's single most important activity: agriculture. What are the possibilities that relevant knowledge can partially remove constraints on these resources?

3.4.1. Fresh water

Let's examine the case for fresh water in some detail. Water is indisputably an essential resource. Several liters ($\sim$2.5–4) of water must be consumed daily if an individual is to stay live. A minimum estimate for total personal use (cooking, bathing, flushing away waste) is 50 l per day (Gleick, 1996). In addition to direct uses, water is essential for crop production.

The current and projected future rates of water use are unsustainable. Presently 1.5–2 billion people fall short of the requirement for personal use. On a global scale, humanity is already using about half of the accessible fresh water for personal, industrial, and (primarily) agricultural purposes (Postel et al., 1996).

Technology could improve the efficiency of water use by agriculture and thus reduce the per-capita requirement. At present, approximately 60% of water diverted to fields for irrigation is actually taken up by the crops which are irrigated, while 40% is lost between the irrigation water source and the plant (Zilberman, 1997). If one accounts for evaporation in reservoirs and conveyance channels, for leaking pipes, and for inefficient irrigation systems, only 25% of all water diverted to irrigation gets into crop plants (World Resources Institute, 1997). If by some miracle of irrigation technology these losses were nearly eliminated (i.e. 99% efficiency were achieved), water use efficiency would rise by a factor of 4 (0.99/0.25). Note that this is a far cry from a factor of 10 increase called for in some technologically optimistic political statements, such as the goal adopted in 1996 at the ministerial level of the

[6] An interesting discussion of this point is provided in Cohen and Zysman (1987), a response to the shift-toward-services claim mentioned in the opening of this paper. The authors point out, with numerous examples, that there are many manufactured goods for which service-type substitutes do not exist.

Environmental Policy Committee of the OECD (Adriaanse et al., 1997).

Of course, genetic engineering may yield varieties of crops which require much less water in the first place, but there are practical limits in this area as well. Certainly genetic engineering is a powerful tool, but crops are still subject to biological constraints. In fact, green revolution strains of high yielding wheat have lower water use efficiency (WUE) than their lower yielding ancestors (Ehdaie et al., 1991), suggesting that the window may be narrow for improving yields and WUE at the same time.[7] In addition, there is a negative feedback loop that may diminish any gains in total WUE that irrigation technology and genetic engineering offer. Evapotranspiration from plants and evaporation from moist ground surfaces is essential to natural cooling. If irrigation systems no longer spill a drop on the ground and plants respire much less, this cooling effect will be greatly reduced (McNaughton and Jarvis, 1991).

More fresh water can be created by treatment of waste water, but reuse of waste water is only possible for the portion of the water supply that is used non-consumptively. Agriculture is by far the largest user of water, and its use is consumptive. One cannot reuse irrigation water that has been evapotranspired.

Finally, there are such possibilities as mining polar ice caps by towing icebergs to places where water is in short supply, and creating more fresh water through desalinization. Because huge amounts of energy are required to tow icebergs or desalinate large quantities of salt water and pump it to where it is needed, such schemes are neither environmentally nor economically feasible in most instances.

In short, with regard to the four questions above as applied to water: (1) it is an essential resource; (2) it is being used unsustainably and becoming scarce in many areas; (3) relevant knowledge can help increase access to water resources and reduce per capita demand, but there are biological and energetic constraints that will sharply limit progress in that area; and (4) the rate of innovation seems far below that required to keep up with demand, which under optimistic assumptions would require humanity to use more than 70% of accessible freshwater by 2025 (Postel et al., 1996).

3.4.2. Fertile soils

The situation with fertile soils is similar, but more complex and less well-measured. Clearly, fertile soils are essential for crop production. Statistics on erosion rates are unreliable, but there is general agreement that in many areas erosion is well above replacement rates (Brown and Wolfe, 1984; Crosson, 1995).

Currently there are three possibilities for augmenting the role played by natural fertile soils. Fertilizers can help maintain fertility, but suffer from economic and biological constraints. High quality topsoil can also now be produced through composting, but its cost (about $50 per cubic meter, or about $50 000 per hectare for a 10 cm layer) is unlikely to be affordable in large-scale agriculture. At the extreme, the possibilities of extensive hydroponic cultivation are much more remote than those of extensive desalinization—the costs of replacing fields with structures for growing basic crops would be vastly prohibitive, even if sustainable systems could be designed. For example, construction of a modern hydroponic system in the US today would cost about a million dollars a hectare, and the system would have high operating costs and be extremely vulnerable to things like power outages (Daily et al., 1997). It is no accident that area under hydroponics is on the order of one millionth of the global cropped area.

Thus, with regard to soil, our answers to the four questions above are: (1) it is essential; (2) it is often used unsustainably; (3) relevant knowledge can help maintain what resources we have and help to rebuild them, but economic and biological constraints are likely to make progress difficult;

[7] The best improvement in WUE after 500 million years of plant evolution is C4 photosynthesis, which has WUE approximately double its evolutionary predecessor, C3 photosynthesis (Björkman, 1971). To improve on this mechanism, the carboxylating enzyme which absorbs the CO_2 would need to be re-engineered to have a much greater affinity for CO_2, or a stomatal membrane would need to be developed that is permeable to CO_2 but not to water vapor. So far, neither evolution nor technology has indicated much promise in this direction.

and (4) the rate of innovation seems far behind the growth in demand implied by the need to at least double food production in the next 50 years.

3.4.3. Energy

Energy has perhaps been analyzed more thoroughly than any other resource (Holdren, 1987; Smith, 1987; Holdren, 1990), and the results, from the perspective of this paper, can be easily summarized. In the context of our four questions again: (1) energy is essential; (2) there are no basic problems of sustaining supplies, although over commitment to some sources (e.g. petroleum) linked with the long time-scales of bringing new sources on line could cause severe future disruptions; there are, however, severe sustainability problems because of the many environmental impacts of overuse (e.g. climate change caused by CO_2 emissions from fossil fuels); (3) relevant knowledge can help to transition to more environmentally benign sources; and (4) the rate of innovation, or at least support of innovation (Holdren, 1990), is declining as the need increases.

3.4.4. Biodiversity

Biodiversity is an essential resource, although the exact proportion of diversity that is essential is unknown (Naeem et al., 1994; Naeem et al., 1996; Tilman et al., 1996). Species and population diversity provides genetic material for crops and medicines, goods such as seafood and timber, and ecosystem services such as pollination, purification of air and water, and flood control (Heywood, 1995; Daily, 1997; Hughes et al., 1999). It is clear that biodiversity is being used unsustainably. Current human-driven species extinction rates are 100 to 1000 times higher than background speciation rates (Pimm et al., 1995), and populations are going extinct at a rate three orders of magnitude higher than species (Hughes et al., 1997).

There are no known large-scale substitutes for biodiversity in most of its ecosystemic roles—for example, helping to stabilize the climate by sequestering carbon, watershed protection, recycling of nutrients, or control of most potential agricultural pests (Ehrlich and Mooney, 1983; Daily, 1997). Although technology may never greatly reduce need for biodiversity, it can play an important role in preserving and restoring population diversity. Knowledge that would allow the restoration of populations in natural areas could restore valuable ecosystem services, and better technologies for storing seeds or other propagules (i.e. gene banks) could help supply the necessary elements for restoration.

With regard to the four questions above as applied to biodiversity: (1) some amount is essential; (2) it is being used unsustainably; (3) knowledge is not likely to reduce the need for biodiversity or replace species diversity, but relevant knowledge can help maintain stocks and rebuild them at the population level; and (4) the rate of innovation in biodiversity preservation is trivial compared to the growth in need for ecosystem services (Daily, 1997).

Knowledge-intensive production can and has yielded enormous efficiency gains in production, such as of electronic devices (which, however, only account for about two percent of gross domestic product). But one must ask the extent to which such gains are plausible for essential resources. This is an empirical question that demands further research, although enough is known to make some scientists skeptical of the possibility of sustaining even today's $P \times A$ level (Daily et al., 1994).

4. How do we attain environmentally beneficial outcomes?

Even though more knowledge does not inevitably lead to environmentally beneficial outcomes, we are convinced that additional knowledge of environmental systems, the assaults upon them, and the human behavior and institutions behind those assaults, is a prime requirement for solving the human predicament. Societies are thus faced with the challenge of ensuring that such new knowledge is developed and implemented.

There seem to be five major obstacles that prevent knowledge from alleviating environmental impacts: (1) lack of incentives to generate environmentally relevant knowledge; (2) lack of accessi-

Table 1
A partial taxonomy of problems and relevant policies

Problem type	Potential policy response
Lack of incentives for generating environmentally relevant knowledge: (a) Non-excludable benefits of knowledge production. (b) Failure to correct environmental externalities leading to inadequate incentives for some types of knowledge.	(a) Produce knowledge publicly, or subsidize private producers of knowledge. (b) Implement corrective taxes or auction permits-to-emit. (c) Securitize the biosphere. (d) Protect intellectual property rights more completely.
Lack of accessibility to knowledge.	Subsidize dissemination of knowledge (education).
Production and distribution of disinformation.	Reduce incentives for disinformation production or distribution.
Misalignment of individual and societal incentives (e.g. the problem of depletion due to open access).	Correct environmental externalities through taxes, subsidies, or the establishment of property rights.
Less than best behavior due to constraints (e.g. credit or political) that prevent individuals, firms, or governments from acting upon the knowledge that they have.	Reform institutions to eliminate or reduce these constraints.

bility to knowledge; (3) competing disinformation; (4) misalignment of individual and social goals; and (5) constraints on the ability to respond to available knowledge. Table 1 outlines these problems and the theoretical policy interventions available. In the remainder of this section, we expand on each of the obstacles, but it is obvious that practical solutions have to be tailored to specific circumstances.

4.1. *Provide incentives for the generation of environmentally relevant knowledge*

Many analyses explain knowledge-growth as resulting from firms' research and development (R&D) expenditures. Firms typically pursue R&D expenditure as a type of investment, devoting funds to R&D in the expectation that the new knowledge gained from such expenditure will produce cost-savings that more than offset the cost of R&D. While many firms engage in R&D on an ongoing basis, there are several reasons why incentives to invest in environmentally-beneficial knowledge may not be sufficient to ensure a sustainable society.

First, knowledge often is not excludable; that is, its benefits are not entirely appropriable by its creators: there is a free-rider problem. Once this new knowledge is obtained, anyone can use this knowledge without paying back the knowledge-generators (researchers) for their efforts. For instance, vector-borne diseases like malaria can often be controlled by environmental management at least as cost effectively as through patentable biotechnological solutions such as vaccines, high tech pesticides, and so forth. One such management technique is to manipulate the timing of flood irrigation of rice paddies to reduce mosquito populations (Rajendran, 1995). In fact, studies indicate that this type of knowledge-intensive irrigation management also increases rice production in nations like Japan with good water control. Because these techniques are not patentable, however, there is less private incentive for such knowledge than is socially desirable. In contrast, patentable biotechnical solutions are profitable, and for this reason are more aggressively pursued.

Economic analysis indicates that to the extent that new knowledge is not fully appropriable, individual firms tend to invest insufficiently in R&D. This suggests a role for public policy. Indeed, policy action in this area could have very large environmental benefits. One theoretical solution to underinvestment in non-excludable activities is to subsidize those activities. This provides a justification for government supported research programs and for the tax-exempt status of non-profit research institutions. In practice, the theoretical solution runs into many obstacles,

however. For example, a strong enough profit motive for the appropriable solution (e.g. biotechnology) can lead to capture of the research agenda of public and non-profit institutions in a field, and exclusion of competing types of research (e.g. preventive environmental health).

A second incentive problem arises when the public sector's failure to correct environmental externalities discourages efforts to discover or develop cleaner technologies. The case of climate change offers an example of this phenomenon. Because there is no carbon tax (i.e. no tax on the climate-related externality from fossil fuel use), there is insufficient reward to producers of low- or non-carbon energy supplies or products. As a result, there is insufficient R&D and knowledge-generation in these non-carbon alternatives. The same can be said for water- and pesticide-sparing agricultural practices. Thus, dealing with environmental externalities produces a side-benefit of stimulating greater efforts to expand the knowledge base for more benign production methods. Conversely, failing to deal with environmental externalities creates a situation in which incentives for generating environmentally friendly knowledge are far too low, as indicated by totally inadequate funding for research on renewable energy sources (Holdren, 1990). Policy responses to close the gap between the private and social costs of resource use range from tax incentives and command and control regulation to expanding property rights and, as discussed below, securitizing the biosphere.

4.2. Improve access to environmentally relevant knowledge

No one has access to all the knowledge that exists, and more and better knowledge will not help if the people and institutions that need the knowledge do not have access to it. Oftentimes, highly attractive solutions to environmental problems are not pursued because the public is not aware of them. For example, few people realize that it may often be more economically sensible to reconstitute or enhance ecosystem services than to pay for technological solutions to environmental problems. For instance, declining water quality in New York City led to a proposal for a water treatment plant that would cost $6–8 billion. But investigation showed that the natural water-purification capacity of the Catskill watershed could be restored for $1–1.5 billion. A decision was made to do the latter, financed by floating a bond issue. The entire process could have been financed by New York opening a watershed savings account funded by paying a fraction of the costs avoided by not constructing a water purification plant. By paying investors in bonds they would have securitized their savings (Chichilnisky and Heal, 1998). The World Bank is now investigating similar projects (involving securitizing the biosphere) for assuring water quality in a number of poor countries. It is imperative that knowledge about ecosystem services (and this economic method of protecting them) be made as widely accessible as possible. Currently, only a small number of agencies and individuals have access to such information.

If the gains of restricted access to knowledge are large enough for a powerful interest group, access to knowledge may be highly restricted, even in democratic, capitalist societies. Since knowledge can confer great power, open and equitable access to it is not something that occurs naturally. Although society as a whole benefits from equitable access to knowledge, someone, somewhere often gains by keeping others in the dark. Perhaps the recent broad-scale attempts to minimize the significance of environmental problems (Ehrlich and Ehrlich, 1996) are a response to the greater availability of basic knowledge about how damaging many profitable activities are to the environment. The theoretical solution to improve access to knowledge is to subsidize dissemination, most likely by education through schools and the public media. In the long run, embedding new knowledge in policies and institutions that mediate human interactions with the environment is critical (Berkes and Folke, 1998). Perhaps surprisingly, the growth of the service economy offers an important opportunity to increase access to relevant knowledge. Consider that roughly $1 out of every $10 spent in retails sales in the US is spent at a handful of chains such as Walmart, Sears, and Target. The fast-food chain, McDon-

alds, operates 23 000 restaurants in 109 countries, selling about 22 000 000 meals daily (Guile and Cohon, 1997). These enormous service providers, and others like them, stand in the center of the life-cycle of thousands of products. Given their purchasing power, such service companies exercise enormous influence on the design and manufacture of the products (as well as the agricultural practices and harvesting of the foodstuffs) they sell. Demands by consumers for environmentally preferable goods and services has, in an increasing number of instances, forced these key service providers to collect environmental information on their goods and services, publicly disseminate the information, and establish minimum standards for their suppliers. Relevant policy responses to promote these private knowledge-creating activities include governmental communication (support of environmental management systems and official recognition of best practices) and direct regulation to require collection and dissemination by service providers of product environmental impacts.

4.3. Counter disinformation

There have probably always been organized campaigns of disinformation in support of powerful people or political parties. An old, but now particularly vexing question for free societies is how the quality of information could realistically (or should ethically) be controlled. Part of the answer clearly lies in improving educational systems, but the ways to accomplish this are not clear. Furthermore, with the increasing flood of information, it is difficult for even well-educated citizens to successfully filter cleverly formulated disinformation.

The problem of disinformation can be mitigated somewhat by the provision of (more reliable) information by recognized scientific groups that embrace accepted professional standards of scientific evidence or policy evaluation. Such information has been provided to good effect by the Intergovernmental Panel on Climate Change, an international organization consisting of over 500 respected physical, natural, and social scientists. The Panel's reports offer an antidote to junk science by articulating the current consensus on the prospects for climate change, by outlining the extent of the uncertainties, and by describing the potential benefits and costs of policies to address climate change.

We need to recognize, however, that difficulties in knowing the difference between environmental information and disinformation are generally worsened, not lessened, by growth (and specialization) in scientific knowledge. Advances in scientific understanding, especially because they always involve uncertainty, make access to much environmentally relevant knowledge more difficult for average citizens and therefore tend to worsen the inequality between them and specialists. Those who want to mislead the public can take advantage of that inequality. Even the openness, honesty, and massive scientific consensus in the IPCC discussions of global warming have not been sufficient to counteract a campaign of disinformation supported by industry money. A flood of TV advertising claiming that global warming is nothing to worry about has certainly confused the public and altered its response to increased knowledge in this area.

Disinformation is distinguished from misinformation by the intent of the information source. Legal measures to control disinformation have very limited scope. Neither slander and libel laws (defamation directed toward a person) nor product liability laws (directed at products) are clearly relevant in the realm of public advocacy or scientific discourse. A general approach that may be useful is again suggested by economic theory. When one cannot observe and punish undesirable behavior, one should try to identify the general incentives for that behavior, and reduce them. For example, more thorough environmental education would reduce the chances that disinformation campaigns would be effective and would increase the chance of damaging backlash against the perpetrators.

4.4. Align individual and societal interests

There is widespread awareness among economists and natural scientists that even when adequate knowledge exists individually, actions

that are rational from an individual's perspective do not always yield socially rational outcomes—that is, individual and social goals (utilities) may be out of alignment. The so-called tragedy of the commons (Hardin, 1968; Bromley, 1991; Arrow, 1996), in which an open access resource is overutilized, is one example of this problem. Unless individual and social incentives are aligned, there is no assurance that environmentally beneficial outcomes will result even when people and firms have complete knowledge and are able to act upon that knowledge. Correction of environmental externalities via taxes, or correction of knowledge spillovers through subsidies, would take us a long way toward alignment of social and individual rationality. But other misalignments exist as well, such as the incentive to not pay for public goods if others will pay for them. Although economic theory again is rich in theoretical solutions to these types of problems, their application to particular circumstances is difficult and beyond the scope of this paper.

4.5. Enhance the capability to respond to knowledge

There are many reasons that individuals, firms, or nations may not be able to do what are in both their best interests and the best interests of the environment. Possessing knowledge and good intentions is not enough to insure that the growth in knowledge will be beneficial for the environment.

For example, credit constraints often prevent individuals from implementing choices that are both good for the environment and good for the individual. Consider solar ovens, especially in the tropics. These devices, which cost from $10 to $150 have numerous benefits. They reduce the quite serious and widespread respiratory and eye ailments that result from cooking with wood or dung. They reduce the time required to gather biomass fuels, which in some areas requires as much as 10–25% of a woman's daily energy expenditure (Dasgupta, 1993). (There are, of course, other constraints ranging from overdesign of the ovens to the roles of cooking fires in social life and home heating). In addition, reduced reliance on wood and dung for fuel slows the rate of deforestation and fertility loss in agricultural soil. But many if not most poor people, without physical collateral, cannot obtain loans with which to purchase these devices, although they would pay for themselves over time. Other forms of collateral, such as the social collateral concept developed by the Grameen Bank in Bangladesh, need to be incorporated into banking practices worldwide. Under this concept, five or six neighbors guarantee repayment of the loan, creating peer and social pressure to repay the loan. Similarly, in industrial countries, some people who wish to live close to where they work and to buy homes that are energy efficient, find that the reduced cost of living that would be created by these choices can not be obtained. Often banks will not grant the larger mortgage needed to buy energy efficient or location-efficient homes, even when energy and commute savings more than pay for the amortized cost of the increased mortgage. This is because standard banking practice is to lend no more than a fixed percentage of gross income, regardless of the buyer's estimated living expenses.

Thus, agents can't act effectively upon their knowledge unless they have the means to invest. Alternative forms of collateral, and more sophisticated rules for determining maximum loan amounts, need to be developed so that all agents, and especially those with limited capital resources, can act upon their knowledge of the world. Policy innovations such as better banking rules and practices are needed to enable agents to act upon available knowledge. We need banks that are different than the ones Will Rogers so aptly described as organizations dedicated to lending money to people who don't need it.

Governments also face these types of constraints. While traveling in East Africa in 1983, Ehrlich witnessed horrific soil erosion in the highlands of Rwanda. Many fields were planted in rows that marched straight up the hillside. In 1991 the Rwandan Minister of Agriculture wrote about this problem, "Population pressure has made us intensify our agriculture and by doing that we have experienced significant soil losses. … We estimate that our arable lands are diminishing each year by about 8000 hectares. … We can produce enough food for 5

million people – but we have 7.3 million people. ... I am afraid that if the rate of population growth continues, we might have serious difficulties.'' Although the Minister of Agriculture knew about soil erosion, and the technical solutions to it, he and his nation were not able to communicate to a young, illiterate, and increasingly desperate and divided population the most basic of erosion control techniques.

Another constraint involves political choice. Public opinion surveys show that many Australians are supportive of the current government's economic policies and are also supportive of stronger climate change policy than the current government has been willing to support. Unfortunately, no political party offers the optimal mix of economic and climate policies. In this case, individuals cannot act effectively upon the environmentally relevant knowledge that they have, presumably, obtained. This example is not atypical of the political choice process. Because individuals don't have the full range of choices (that is, they can't choose each policy position independent of other policy positions), they are not able to take full advantage of knowledge that they possess. To some degree this problem is inherent in the structure of republics, since people are constrained to vote for individuals or platforms, but so is the power of an informed public to change the mix of policies advocated by politicians or political parties.

Finally, there exist enormous political mobilization problems, even when environmental knowledge is accessible. Consider a situation where, overall, a policy would produce aggregate net social benefits: the aggregate gains to those who benefit would exceed the aggregate losses to those who lose. Suppose that the gains are distributed very broadly, so that the benefits to each potential winner are quite small, while the losses are distributed quite narrowly, so that each potential loser has a large stake in the outcome. If there are any hurdles or fixed costs connected with becoming involved politically, the potential losers are likely to mobilize more than the potential winners. Thus the policy could well be blocked politically, despite its potential to generate net social benefits. This political mobilization bias can explain the ability of special interests to prevent the introduction of socially desirable environmental policies (as well as other beneficial policies outside of the environmental policy arena). There is no obvious solution to this important problem, though reducing the cost of political involvement could reduce its magnitude.

5. Summary and conclusions

It is not a straightforward task to determine if a knowledge explosion is actually occurring. Clearly there has been a recent information explosion, but if one accounts for the quality of such information and the extent to which it can or cannot be translated into human understanding, the evidence for a knowledge explosion becomes mixed. Even if a knowledge explosion is taking place, this does not necessarily imply growth of environmentally beneficial knowledge. And even if there is growth in environmentally beneficial knowledge, it does not follow that this knowledge is actually put into practice.

It is unclear if recent knowledge has had a positive or negative net impact on the environment. The historical record suggests that past advances in knowledge have often been detrimental to the environment. Although the future may not perfectly mimic the past, there are reasons to be skeptical as to the extent to which knowledge-growth will attenuate environmental problems. Population growth rates are declining over much of the planet, but per capita consumption continues to rise. An examination of essential natural resources suggests there are fundamental limits to the extent to which advances in knowledge, in the presence of continued growth of population and per-capita consumption, can prevent the depletion of these resources and the associated environmental problems. The ability to shift economic activity from goods toward services only partly eliminates the need for fundamental natural resources and must eventually encounter limits. Knowledge can never be a sole antidote to the increasing pressures on the environment posed by increasing population and per-capita consumption. These constraints are largely unacknowledged in the political arena.

Our investigation emphasizes the crucial role of public policy in helping generate knowledge that can benefit the environment and in channeling that knowledge to good effect. We cannot afford to sit back and wait for knowledge to take care of everything: private markets often fail to generate sufficient investments in knowledge or lead to appropriate diffusion or application of knowledge. We need public policies that can provide incentives to generate environmentally relevant knowledge, improve access to knowledge, and discourage or weaken the effectiveness of disinformation and junk science. In addition, institutions must change so that people have the means to act upon their knowledge, and policies must be adopted which increase the likelihood that individually rational actions will add up to socially desirable environmental outcomes.

We are pleased to conclude by noting that increasingly academics, at least, are more aware now than in years past of the importance of finding ways to accelerate such outcomes. Cooperative efforts across disciplinary boundaries, such as the conference on Managing Human-Dominated Ecosystems held at the Missouri Botanical Garden and attended by ecologists, economists, business people, attorneys, and others, are increasingly being aimed at seeking solutions to these difficult problems.

Here, as in many other policy contexts, the devil is in the details. More needs to be known about putting general theoretical solutions (such as we have outlined) into practice, and there is no time to waste.

Acknowledgements

We are grateful to Chris Field for information about water use efficiency and to John Gowdy, John P. Holdren, and James Salzman for helpful comments.

References

Adriaanse, A., Bringezu, S., Hamond, A., Moriguchi, Y., Rodenburg, E., Rogich, D., Schutz, H., 1997. Resource Flows: The Material Basis of Industrial Economies. World Resources Institute, Washington, DC.

Arrow, K.J., 1996. Foreword. In: Hanna, S.F., Folke, C., Maxler, K.-G. (Eds.), Rights to Nature: Ecological Economic, Cultural, and Political Principles of Institutions for the Environment. Island Press, Washington, DC.

Berkes, F., Folke, C., 1998. Linking Social and Ecological Systems. Cambridge University Press, Cambridge, MA.

Björkman, O., 1971. Comparative photosynthetic CO2 exchange in higher plants. In: Hatch, M.D., Osmond, C.B., Slatyer, R.O. (Eds.), Photosynthesis and Photorespiration. Wiley-Interscience, New York, pp. 18–32.

Bromley, D.W., 1991. Environment and Economy: Property Rights and Public Policy. Basil Blackwell, Cambridge, MA.

Brown, L., Wolfe, E., 1984. Soil Erosion: Quiet Crisis in the World Economy. Worldwatch Institute, Washington, DC.

Chichilnisky, G., 1996. The economic value of Earth's resources. Trends Ecol. Evol. 11, 135–140.

Chichilnisky, G., 1998. The knowledge revolution. J. Int. Trade Econ. Dev. 7, 39–54.

Chichilnisky, G., Heal, G., 1998. Economic returns from the biosphere. Nature 391, 629–630.

Cohen, S.S., Zysman, J., 1987. Manufacturing Matters: The Myth of the Post-Industrial Economy. Basic Books, New York, New York.

Colborn, T., Dumanoski, D., Myers, J.P., 1996. Our Stolen Future. Dutton, New York.

Crosson, P., 1995. Soil erosion estimates and costs. Science 269, 461–464.

Daily, G.C., 1995. Restoring value to the world's degraded lands. Science 269, 350–354.

Daily, G.C., 1997. Nature's Services. Island Press, Washington, DC.

Daily, G.C., Ehrlich, A.H., Ehrlich, P.R., 1994. Optimum human population size. Pop. Environ. 15, 469–475.

Daily, G.C., Ehrlich, P.R., 1992. Population, sustainability, and Earth's carrying capacity. BioScience 42, 761–771.

Daily, G.C., Matson, P.A., Vitousek, P.M., 1997. Ecosystem services supplied by soil. In: Daily, G.C. (Ed.), Nature Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, DC, pp. 113–132.

Dasgupta, P., 1993. An Inquiry into Well-being and Destitution. Oxford University Press, Oxford.

Drucker, P.F., 1993. Post-capitalist Society. Harper-Collins, New York.

Ehdaie, B., Hall, A.E., Farquhar, G.D., Nguyen, H.T., Waines, J.G., 1991. Water-use efficiency and carbon isotope discrimination in wheat. Crop Sci. 31, 1282–1288.

Ehrlich, P.R., 1995. The scale of the human enterprise and biodiversity loss. In: Lawton, J.H., May, R.M. (Eds.), Extinction Rates. Oxford University Press, Oxford.

Ehrlich, P.R., Daily, G.C., Daily, S.C., Myers, N., Salzman, J., 1997. No middle way on the environment. The Atlantic Monthly, 98-104.

Ehrlich, P.R., Ehrlich, A.H., 1981. Extinction: The Causes and Consequences of the Disappearance of Species. Random House, New York.

Ehrlich, P.R., Ehrlich, A.H., 1990. The Population Explosion. Simon and Schuster, New York.
Ehrlich, P.R., Ehrlich, A.H., 1991. Healing the Planet. Addison-Wesley, Reading, MA.
Ehrlich, P.R., Ehrlich, A.H., 1996. Betrayal of Science and Reason: How Environmental Anti-science Threatens our Future. Island Press, Washington, DC.
Ehrlich, P.R., Ehrlich, A.H., Daily, G.C., 1995. The Stork and the Plow: The Equity Answer to the Human Dilemma. Putnam, New York.
Ehrlich, P.R., Ehrlich, A.H., Holdren, J.P., 1977. Ecoscience: Population, Resources, Environment. W.H. Freeman, San Francisco, CA.
Ehrlich, P.R., Holdren, J., 1971. Impact of population growth. Science 171, 1212–1217.
Ehrlich, P.R., Mooney, H.M., 1983. Extinction, substitution and ecosystem services. BioScience 33, 248–254.
Gleick, P., 1996. Basic water requirements for human activities: meeting basic needs. Water Int. 21, 83–92.
Guile, B., Cohon, J., 1997. Sorting out a service-based economy. In: Chertow, M., Esty, D. (Eds.), Thinking Ecologically. Yale University Press, New Haven.
Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.
Heywood, V.H., 1995. Global Biodiversity Assessment. Cambridge University Press, Cambridge.
Holdren, J.P., 1987. Global environmental issues related to energy supply. Energy 12, 975–992.
Holdren, J.P., 1990. Energy in transition. Sci. Am. 263, 156–163.
Horgan, J., 1996. The End of Science. Addison-Wesley, Reading, MA.
Hughes, J.B., Daily, G.C., Ehrlich, P.R., 1997. Population diversity: its extent and extinction. Science 278, 689–692.
Hughes, J.B., Daily, G.C., Ehrlich, P.R., 1999. The loss of population diversity and why it matters. In: Raven, P.H. (Ed.), Nature and Human Society. National Academy Press, Washington, DC, in press.
Intergovernmental Panel on Climate Change, 1996. Climate Change 1995—The Science of Climate Change: Contribution of Working Group I to IPCC Second Assessment Report. Cambridge University Press, Cambridge, UK.
Kane, H., 1996. Shifting to sustainable industries. In: Brown, L.R. (Ed.), State of the World, 1996. W.W. Norton, New York, pp. 152–167.
Mankiw, N.G., Romer, D., Weil, D.N., 1992. A contribution to the empirics of growth. Q. J. Econ. 107, 407–437.
McNaughton, K.G., Jarvis, P.G., 1991. Effects of spatial scale on stomatal control of transpiration. Agric. For. Meteorol. 54, 279–302.
Myers, N., 1979. The Sinking Ark. Pergamon Press, New York.
Naeem, S., Hakansson, K., Lawton, J.H., Crawley, M.J., Thompson, L.J., 1996. Biodiversity and plant productivity in a model assemblage of plant species. Oikos 76, 259–264.
Naeem, S., Thompson, L.J., Lawler, S.P., Lawton, J.H., 1994. Declining biodiversity can alter the performance of ecosystems. Nature 368, 734–737.
Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres Jr, F., 1998. Fishing down marine food webs. Science 279, 860–863.
Pimm, S.L., Gittleman, J.L., Brooks, T.M., 1995. The future of biodiversity. Science 269, 347–350.
Porat, M., 1977. The Information Economy: Definition and Measurement. Office of Communications, US Department of Commerce, Washington, DC.
Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Science 271, 785–788.
Rajendran, R., 1995. Prospects and problems of intermittent irrigation for control of vector breeding in rice fields in southern India. Ann. Tropical Med. Parasitol. 89, 541–549.
Rejeski, D., 1997. An incomplete picture. Environ. Forum 14, 26–34.
Romer, P.M., 1986. Increasing returns and long run growth. J. Politic. Econ. 94, 1002–1037.
Romer, P.M., 1990. Endogenous technological change, J. Politic. Econ. 98, S71-S102.
Safina, C., 1997. Song for the Blue Ocean. Henry Holt, New York.
Sagoff, M., 1997. Do we consume too much? The Atlantic Monthly, 80–96.
Sahlins, M., 1972. Stone Age Economics. Aldine, Chicago.
Schneider, S., 1989. Global Warming. Sierra Club, San Francsico.
Schneider, S.H., 1997. Laboratory Earth: The Planetary Gamble We Can't Afford to Lose. BasicBooks, New York.
Smith, K., 1987. Biofuels, Air Pollution, and Health: A Global Review. Plenum, New York.
Stern, P.C., Dietz, T., Ruttan, V.W., Socolow, R.H., Sweeney, J.L., 1997. Environmentally Significant Consumption: Research Directions. National Academy Press, Washington, DC.
Tilman, D., Wedin, D., Knops, J., 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature 379, 718–720.
Wilson, E.O., 1992. The Diversity of Life. Harvard University Press, Cambridge, MA.
World Commission on Environment and Development, 1987. Our Common Future. Oxford University Press, New York.
World Resources Institute, 1997. Frontiers of Sustainability. Island Press, Washington, DC.
Zilberman, D., 1997. Economics and sustainable development. In: Rosen, D., Tel-Or, E., Hadar, Y., Chen, Y. (Eds.), Modern Agriculture and the Environment. Kluwer, Boston, pp. 555–566.