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ECONOMIC PATHWAYS TO ECOLOGICAL SUSTAINABILITY

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To Appear

Economic pathways to ecological sustainability

by

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With the arrival of the new millennium comes consensus among a broad spectrum of scholars that the scope and magnitude of environmental problems threaten the sustainability of Earth's life-support systems (see e.g. Lubchenco et al. 1991, Vitousek et al. 1997, Lubchenco 1998). This conclusion has long been argued by ecologists (e.g. Ehrlich and Ehrlich 1981), but they are no longer alone. A growing number of interdisciplinary scientific reports reflect new information and broader concerns. For example, the United States President's Committee of Advisors on Science and Technology (PCAST) recently expressed concern that the composition and scale of economic activities in the USA are changing the chemistry of the nation's land, water, and atmosphere so dramatically that some of these changes are adversely affecting its natural capital and thus the ecosystem services required to support its population sustainably (PCAST 1998). Earlier, the 1992 World Development Report of the World Bank summarized and recommended a number of methods developed in recent years by which the protection, promotion, and use of environmental natural resources can be brought into the orbit of economic reasoning (see World Bank 1992). A report from the United Nation's Environment Programme points out the interlinkages among environmental, economic health, and equity issues (Watson and al. 1998); and very recently, the United States National Science Board declared that environmental research, education, and assessment should be the highest priorities of the National Science Foundation (NSB 1999).

If the core problems of the environment are in great measure ecological, their causes and consequences are largely anthropogenic. This means that appropriate solutions need to involve partnerships among scientists from a broad range of disciplines. Individuals from all branches of science have long recognized this challenge, but a deep chasm seems to have separated many of them. To be sure, different disciplines have different languages, different ways of thinking, and different assumptions. For this reason, it takes time to build effective bridges. In the last few years, however, there has been a virtual phase transition, in that an increase in trust and mutual respect has led to widespread cooperation and collaboration among natural and social scientists engaged in the study of environmental problems. New institutions, societies and journals have been established [1]. Indeed, the points drawn in the PCAST, UNEP, and NSB reports on the economics of the environment are a natural outgrowth of the findings of natural scientists (e.g. Ehrlich et al. 1977, Wilson 1992, Cohen 1995, Daily 1997), social scientists (e.g., Kneese et al. 1972, Mäler 1974, Baumol and Oates 1975, Dasgupta 1982, Dasgupta and Mäler 1991) and, more recently, of partnerships between the disciplines (e.g. Arrow et al. 1995, Daily et al. 1998, Levin et al. 1998). Although much has been accomplished, a great deal more needs to be done. This paper focuses on the fertile and expanding common ground between ecologists and economists.

Individuals and groups make use of the environmental resource base for large numbers of reasons. Their rates of use depend on the costs and benefits people perceive or incur in utilizing the resources. In other words, the relative costs and benefits give rise to the incentives people have for protecting, promoting, or destroying the various forms of natural capital. These costs and benefits depend not only upon the size and composition of the resource base, but also upon the institutional structure within which people operate. So, for example, if economic transactions are carried out exclusively in markets, and if—for whatever reasons—prices for the use of ecosystem services are nonexistent or low, people would be expected to be profligate in their use of such services. It follows that an overarching environmental problem is to determine what kinds of social institutions would be expected best to protect and promote the environmental resource base upon which life depends and thrives.

Progress in our understanding of the problem has been made in recent years in part because of increased attention to a number of distinct sub-problems that need to be addressed first. In this article we sketch those we believe to be of particular importance. Although they are closely related, we discuss them in turn for pedagogical reasons.

In the next section we set the scene by reporting a few global statistics on global food availability and prospects and show that, because they involve different considerations, global environmental concerns need to be contrasted from local environmental concerns. The point is that a study of local environmental problems brings to light the wide variety of institutional structures that are currently in operation and that need to be understood and improved.

Subsequently, we show that the prevailing structure of prices and standard-of-living indices in common usage are deficient. In particular, we show how they mislead decision-makers—be they households, private firms, or governments. As we have already noted, this is a key issue, for it gives rise to the structure of incentives people have in making use of the environment around them. However, the relative economic values of different natural resources depend also on the extent to which such resources can substitute for one another in economic activity and, more crucially, in preserving life itself. Consequently, we next comment on the notion of substitutability among natural resources. Finally we return to our central theme—that environmental problems in the modern world are a symptom of a combination of ignorance and institutional failure. The final section offers some general remarks on an agenda for future research.

Local vs. global constraints

Although environmental degradation at the geographically localized level has occurred from time to time since even before recorded history, its global reach is a more recent phenomenon. A near-50 percent increase in world population, combined with a doubling of gross world product per head, by the year 2040, would create substantial additional "stresses" in both local and global ecosystems (e.g., Botsford et al. 1997, Chapin III et al. 1997, Matson et al. 1997, Vitousek et al. 1997, Watson and al. 1998). For example, global "demand" for food could easily double over the period 1990-2030, with two-and-a-half to three-fold increases in demand in the poorest countries. Of particular concern are Asia and Africa where, over the next fifty years, plant-derived food-energy requirements are expected to increase by factors of 2.3 and 5, respectively, with a more-than-sevenfold increase expected in some countries (Pinstrup-Anderson 1994, Crosson and Anderson 1995, FAO 1996). These figures do not include the inevitable increases in the demand for non-food commodities that would accompany increases in population and in GNP (Gross National Product). For all of these reasons, considerable attention has been devoted in recent years to global-scale environmental problems.

The prospects for a maintaining our quality of life in the face of the predicted increases in the scale of the human enterprise depend on our ability to manage constraints on the supplies of production inputs and on the environmental consequences of the use of these inputs. These constraints are not present uniformly across the globe. Moreover, local problems of production and distribution can be difficult to counter, even when global supplies are adequate, because too many people are too poor. To ask merely whether global production of goods and services can be increased to meet future demands in a sustainable way misses much of the question. For example, food scarcity manifests itself locally, so efforts to alleviate it must be tailored to local circumstances. To do otherwise is akin to treating a sick person on the basis of global health statistics. A related problem involves the growing inequities associated with access to human services (e.g., due to an increasing variance in the distribution of income and wealth).

Although correct diagnosis of the problems that lie at the population-consumption-environment nexus must be locally relevant, appropriate treatment may also require regional and global mechanisms and support. For example, soil erosion may not currently be a serious threat to global agricultural capacity, but at local levels in various parts of the world it presents major problems to the people affected. Similarly, decisions concerning fertility, education, child-care, food, work, health care, and the use of local environmental resources are, in large measure, reached and implemented within households that face constraints shaped, in part, by national and international policies and the state of the local environment. The influence of household decisions is felt through local interactions (e.g., intra-village and village-town trades), and later percolates up to the global level. Recent work has identified a variety of circumstances that are shaped by positive-feedback mechanisms that drive poverty, hunger, high fertility, resource degradation, and civic disconnection at the local level, even while national (and not merely global) income is rising (see, e.g., Dasgupta and Mäler 1991, Dasgupta 1993, Cleaver and

Schreiber 1994, Dasgupta 1995, Dasgupta 1998). This fact suggests four interrelated conclusion. (1) Obtaining reliable projections of global economic prospects requires adoption of local, contemporary perspectives. (2) Environmental problems go beyond those that are aired during international negotiations; myriad local environmental problems are in constant need of attention by local people. (3) The assertion often made by development economists (see, e.g., Bardhan 1996, Ray 1998), that current-day environmental and population problems in poor countries are only a manifestation of poverty, is misleading; because each of the problems influences the others, none is a prior cause of the others. (4) In malfunctioning institutions the prices that households face for the use of various services don't reflect the social scarcity values of those services. This problem of inadequate inclusion of social costs in pricing goods and services is a central one in the valuation of ecosystem services, laying the foundation for the considerations of the next section.

Economic valuation of ecosystem services

Why is there a special need to value ecosystem services? Why can we not rely on markets to guide decisions, be they global or local, in the way we do for so many other goods and services? Or to put the matter in another way, why aren't markets an adequate set of institutions for protecting the environment?

The reason is that for many environmental resources markets simply do not exist. In some cases, this is because they have historically been free to the taker. In other cases, it is because the costs of negotiation and monitoring are too high. Examples are provided by economic activities that are affected by ecological interactions involving long geographical distances (e.g., the effects of uplands deforestation on downstream activities hundreds of miles away or the effects of excessive nutrient run-off from inland agricultural or livestock activities on harmful algal blooms in the coastal zone) or large temporal distances (e.g., the effect of carbon emission on climate in the distant future, in a world where forward markets are non-existent because future generations are not present today to negotiate with us). In other cases (e.g., the atmosphere, aquifers, and the open seas), the nature of the physical situation (viz. the migratory nature of the resource) makes private property rights impractical and so keeps markets from existing; while in yet others (e.g. biodiversity see Perrings et al. 1995), ill-specified or unprotected property rights prevent the existence of markets, or make them function improperly even when they do exist. In short, environmental problems are often caused by market failure (but see the penultimate section).

Problems arising from an absence of forward markets for "transactions" between the present generation and the distant future are no doubt ameliorated by the fact that we care about our children's well-being and know that they, in turn, will care for theirs, in an intergenerational sequence. However, our concern for our own well-being still likely cheats future generations. especially when information about the present is more certain than that about the future. Thus not only intragenerational, but also intergenerational, equity must underlie our valuations (Solow 1991). This is why many economists have argued that market rates of interest do not reflect social discount rates (see, e.g. Lind 1982, Arrow et al. 1996, Dasgupta 1999, Portney and Weyant 1999). In short, market failure involves not only misallocation of resources in the present, but also misallocation across time.

Since markets cannot be relied upon to provide us with prices that would signal true environmental scarcities, there is a need for techniques that would enable us to determine such prices. A great deal of work in environmental and resource economics has been directed at discovering methods for estimating notional prices, also often called accounting prices, that could be used by decision-makers. But for the most part, although practical methods have been developed for estimating the accounting prices of amenities (see, e.g. Mitchell and Carson 1989), relatively few exist for the multitude of ecosystem services that constitute our life-support systems. There is a great deal to be done in the development of valuation techniques for different categories of resources and in different institutional settings.

Nonetheless, it is clear that current frequently used indicators of social well-being (e.g., gross national product per head, life expectancy at birth, and the infant survival rate) do not reflect the impact of economic activities on the environment. In particular, indices of the standard of living such as per capita GNP pertain specifically to commodity production and do not fully account for the use of natural capital in the production process. Hence, statistics on past movements of gross national product reveal nothing about the resource stocks that remain. In particular, they do not make clear whether increases in per capita GNP are being realized by means of a depletion of the resource base (for example, if increases in agricultural production are being achieved by "mining" the soil).

Environmental and resource economists have shown how national accounting systems need to be revised to include the value of the changes in the environmental resource base that occur each year due to human activities (see, e.g., Mäler 1974, Dasgupta and Heal 1979). To manage properly, we need to determine the severity and consequences of resource degradation in the various locations of the world, and specifically if current economic activities are unsustainable. Unfortunately, the practice of national-income accounting has lagged so far behind its theory that we have little idea of the facts. It is, therefore, entirely possible that time trends in such commonly used socio-economic indicators as GNP per head, life expectancy at birth, and the infant survival rate give a singularly misleading picture of movements of the true standard of living.

To state the matter succinctly, we contend that current-day estimates of socio-economic indicators are biased and misleading because the accounting values of changes in the stocks of natural capital are not taken into account. Because their accounting prices are not available, environmental resources on site are frequently regarded as having no value. This amounts to regarding the depreciation of natural capital as inconsequential. However, because these resources are scarce goods, their accounting prices are positive. So, if they depreciate, there is a social loss. This loss means that profits attributed to projects that degrade the environment are frequently greater than the social profits they generate. Estimates of their rates of return are higher than their true rates of return. Wrong sets of investment projects therefore may get selected, in both the private and public sectors: resource-intensive projects look better than they actually are.

The extent of such bias in investment activities will obviously vary from case to case, and from country to country. But it can be substantial. For example, in their work on the depreciation of natural resources in Costa Rica, Solorzano et al. (1991) estimated that in 1989 the depreciation of three resources—forests, soil, and fisheries—amounted to about 10 percent of gross domestic product and over one-third of gross capital accumulation.

The bias is also problematic for the prior stage of research and development. When environmental resources are underpriced (in the extreme, when they are not priced at all), there is little incentive on anyone's part to develop technologies that would economize their use. So the direction of technological research and technological change are systematically directed against the environment. Consequently, environmental "cures" are sought once it is perceived that past choices have been damaging to the environment, whereas "prevention", or input reduction, would have been the better choice. To give an example, Chichilnisky and Heal (1998) compared the costs of restoring the ecological functioning of the Catskill Watershed ecosystem in New York State, to the costs of replacing the natural water purification and filtration services the ecosystem has provided in the past by building a water-purification plant costing 8 billion US dollars. They have shown the overwhelming economic advantages of preservation over construction: Independent of the other services the Catskill watershed provides, and ignoring the annual running costs of 300 million US dollars for a filtration plant, the capital costs alone showed a more than 6-fold advantage for investing in the natural-capital base.

It is worth emphasizing that the purpose of estimating environmental accounting prices is not to value the entire environment; rather, it is to evaluate the benefits and costs associated with changes made to the environment due to human activities. Prices, whether actual or merely notional, have significance only when there are potential exchanges from which choices have to be made (for example, when one has to choose among alternative investment projects). Thus, the statement that a particular act of investment can be expected to degrade the environment by, say, 1 million dollars annually has meaning, because it says, among other things, that if the investment were not to be undertaken, humanity would enjoy an additional 1 million dollars of benefits in the form of environmental services, which must be weighed against any benefit. The statement also has operational significance: the estimate could (and should) be used for calculating the rate of return attributable to the investment in question.

Contrast such an estimate of the value of an incremental change in the environmental resource base with the one that says that, world-wide, the flow of environmental services is currently worth, in total, approximately 33 trillion US dollars annually (Costanza et al. 1997). The former is meaningful because it presumes that humanity will survive the incremental change and be there to experience and assess the change. The reason the latter should cause us to balk is that if crucial environmental services were to cease, life would not exist. But then who would be there to receive 33 trillion dollars of annual benefits if humanity were to exchange its very existence for them? Almost paradoxically, perhaps, the value of all the world's ecosystems has no meaning and, therefore, is of no use, even though the value of incremental changes to those ecosystems not only has meaning—it also has use.

Non-convex processes, biodiversity and substitution possibilities

There are further reasons why markets can't be expected to function well for environmental resources. A major achievement of modern economics has been to show that there are many virtues in a competitive market mechanism in economies where the transformation of goods and services into further goods and services is governed by <u>linear</u> processes or possibly by nonlinear but <u>convex</u> ones. But when one talks of "stress" and "positive-feedback mechanisms," as we did earlier, one refers to systems characterized by <u>non-convex processes</u>. (A process is said to be <u>convex</u> if, given any two time paths that are feasible under the process, all time paths that are weighted averages of the two (with positive weights) are also feasible (see Koopmans 1957). It is important to note that non-convex processes can govern both global and local systems. Indeed, even if a large-scale ecosystem did not show signs of stress, local ones could, and often do, display such signs. There are also extant records of local ecosystems having collapsed in the past, such as at Easter Island.

The assumption of linearity in economic transformation possibilities is related to the idea that for every commodity that can be transacted, there are close substitutes lying in wait. The latter assumption, if true, would imply that even as constraints increasingly make their presence felt on any one resource base, humanity could move to other resource bases. The enormous additions to the sources of industrial energy (successively human power, animal and wind power, timber, coal, oil and natural gas and, most recently, nuclear) that have been realized are a prime historical illustration of this possibility.

The assumption of linearity continues to be reasonable in many spheres of activity, but it becomes sorely stretched when applied to activities that encroach upon ecosystems on a greater spatial scale. Ecosystem services are provided as a by-product of the functioning of the ecosystem. They are thus partly dependent upon the identity of the flora, fauna and microbes composing the ecosystem. We thus distinguish the resource base of an ecosystem (i.e, its structure or composition) from its functioning.

Degradation of the resource base (e.g. destruction of native populations of flora and fauna) may affect not only the volume and quality of those services, but also the "resilience," of an ecosystem (Holling 1973, Holling 1986). By resilience we mean the capacity of the system to absorb disturbances, or perturbations, without undergoing fundamental changes in its functional characteristics. (Recovery from disturbances can be costly, in some cases impossible. In short, such "flips" can in many cases be regarded as irreversible (see for example, Levin 1999). If a system loses its resilience, it can flip to a wholly new state when subjected to even a small perturbation (see, e.g., Wilson 1992, Holling et al. 1995, Walker 1995, Levin et al. 1998). One way to interpret an ecosystem's loss of resilience is to view it as having moved to a new stability domain, thereby being captured by a different attractor. Examples include sudden changes in the character of shallow lakes (e.g., from clear to eutrophied water), as a result of increases in the input of nutrients (Carpenter et al. 1989, Scheffer 1997) and the transformation of grasslands into shrublands, as a consequence of non-adaptive cattle-management practices (Perrings and Walker 1995). Human populations can be subject to distress and suffering from unexpected flips in their local ecosystems. Fishermen on Lake Victoria and the nomads in the now-shrublands of southern Africa are examples from recent years.

Emerging information about biodiversity (Mooney et al. 1995, Chapin III et al. 1997) is immediately relevant to our consideration of non-convex processes. It is a popular belief among some segments of society that the utilitarian value of biodiversity is located mainly in the potential uses of chemical and genetic material (e.g., for pharmaceutical or engineering purposes). Preservation of biodiversity is seen as a way of holding a diverse portfolio of assets with uncertain payoffs. But it is increasingly being appreciated that biodiversity, appropriately conceived, is also essential for the maintenance of a wide variety of services on which humans and, indeed, the resiliency of our very life support systems depend (UNEP 1995, Daily 1997). This recognition has an important corollary: To rely upon substitutability among natural resources in commodity production in order to minimize the utilitarian importance of biodiversity, as is frequently done (e.g., Simon 1981, Simon 1994), is scientifically flawed. First of all, without biodiversity, substitutability is lost entirely. And more fundamentally, certain species and groups of species play unique roles in the functioning of ecosystems, and thus have no substitutes. Preservation of biodiversity is hence important both to provide unique services, and also to provide insurance against the loss of similarly functioning species (Chapin III et al. 1995).

Institutional failure and ecosystem destruction

These observations tell us why markets cannot be relied upon to generate correct signals of resource scarcity, nor therefore to generate signals that would alert us to impending shifts in the stability regimes of ecosystems.

In fact, of course, traditional societies have rarely depended upon markets for allocating environmental resources. The study of local environmental problems has revealed the wide variety of institutional structures that have evolved in different locations, in part in response to environmental scarcities. To give only one example, both domestic energy- and water-use in urban USA are based on monetary transactions with commercial suppliers and local authorities. In contrast, in rural sub-Saharan Africa and the Indian sub-Continent they are widely based on communally-owned resources, such as woodlands, rivers, water-holes, and wells. The structure of incentives in the former is based on prices, while in the latter it is built on social norms (Jodha 1986, Ostrom 1990, Dasgupta 1993). But just as markets can fail to operate effectively, giving rise to wrong prices, so too can social norms erode under changing circumstances, thus removing the incentives people in a given location previously had for nurturing their resource-base (Dasgupta 1995).

Ecosystem degradation can also occur because of bad government policies, for example, because of wrong tax policies. (Binswanger (1991) argues that government policies in Brazil regarding agricultural income and land ownership provided incentives for deforestation in the Amazon basin.) We may, therefore, put the matter more generally: an underlying cause of environmental degradation is institutional failure. Indeed, the various types of institutional failure pull in different directions and are together not unrelated to an intellectual tension between the concerns people harbor about global environmental problems, such as global warming and acid rain, which sweep across regions, nations and continents, and regional and local issues, such as, for example, the decline in firewood or water resources that are specific to the needs and concerns of the poor in a small village community. Environmental problems present themselves differently to different societies. Some individuals identify environmental problems with population growth, while others identify or associate them with wrong sorts of economic growth. Others view them through the spectacle of poverty. There is no single correct perspective; rather, there is a large collection of challenges and answers, some global, some regional, many local.

For years, environmental and resource economists have responded to this interrelationship by identifying desirable institutional reforms in a case-by-case manner. Alterations to prevailing structures of property rights, the imposition of environmental and resource taxes, environmental regulations and policies, local-community control, and various other devices that change individual and group incentives have been much discussed and implemented. Contrary to what is frequently suggested in popular writings on environmental matters, the tools of modern economics are not restricted to the study of convex systems. Many of the lessons drawn have been put into use, most especially in the western industrial countries.

However, less research has been conducted on the economics of local ecosystems in poor societies. There is a reason for this. Because economic systems often do not generate signals that would alert the public to growing resource scarcity (a case of institutional failure), it can be a very difficult matter for those who suffer from the economic consequences of the scarcity to get an environmental problem placed on the agenda of public discourse. In poor countries, for example, there are strong links between household poverty, local environmental deterioration, and a weak political voice (see, e.g., Dasgupta 1993). As in many other aspects of life, the political economy of the matter, and in particular governance, is at the heart of many environmental problems.

Conclusion

The challenges of sustainability cannot be the province of ecologists or economists alone, but must involve collaboration among diverse disciplines. We must understand better the linkages between Nature and the services it provides society. This will involve a deeper understanding of how biodiversity and ecosystem functioning are coupled. We must find ways to translate this knowledge into economic terms, and to utilize that information to build strategies for achieving sustainability. This program is in part political, and in part scientific. These two aspects are, however, interconnected; the successful implementation of political solutions must be informed by knowledge not only of the dynamics of ecosystems, but also of the dynamics of humans and their societies.

The roots of global environmental problems are at the local level, and linking local with global perspectives is essential to their solution. Furthermore, global indicators commonly in use fail to represent declines in environmental resources and, consequently, the true costs to societies. Institutional reforms are essential to make the system work—reforms that will tighten feedback loops that encourage or discourage particular activities, creating incentives for individuals and groups to operate in the common good.

Footnote

[1] Examples are Resources for the Future and the World Resources Institute, both based in Washington, D.C.; and the Beijer International Institute of Ecological Economics of the Royal Swedish Academy of Sciences, Stockholm. There are now two professional associations engaged in this field of activity: the International Association of Environmental and Resource Economics and the International Society for Ecological Economics. Prominent journals include the Journal of Environmental Economics and Management, Ecological Economics, and Environment and Development Economics.

References

Arrow K, Bolin B, Costanza R, Dasgupta P, Folke C, Holling C, Jansson B-O, Levin SA, Mäler K-G, Perrings C, and Pimentel D. 1995. Economic growth, carrying capacity, and the environment. Science 268: 520-521.

Arrow KJ, Cline WR, K.-G. M, Munasinghe M, Squitieri R, and Stiglitz JE. 1996. Intertemporal equity, discounting, and economic efficiency in Bruce JP, Lee H, and Haites EF, eds. Climate Change 1995: Economic and Social Dimensions of Climate Change, Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge: Cambridge University Press.

Bardhan P. 1996. Research on poverty and development twenty years after redistribution with growth. Proceedings of the Annual World Bank Conference on Development Economics 1995. Supplement to the World Bank Economic Review and the World Bank Research Observer: 59-72.

Baumol WM, and Oates WE. 1975. The Theory of Environmental Policy: Externalities, Public Outlays and the Quality of Life. Englewood Cliffs, NJ: Prentice Hall.

Binswanger H. 1991. Brazilian policies that encourage deforestation in the Amazon. World Development 19: 821-829.

Botsford LW, Castilla JC, and Peterson CH. 1997. The management of fisheries and marine ecosystems. Science 277: 509-515.

Carpenter SR, Ludwig D, and Brock WA. 1989. Management of eutrophication for lakes subject to potentially irreversible change. Stockholm, Sweden: Beijer International Institute of Ecological Economics.

Chapin III FS, Lubchenco J, and Reynolds HL. 1995. Biodiversity effects on patterns and process of community in UNEP Global Biodiversity Assessment. Cambridge: Cambridge University Press.

Chapin III FS, Walker BH, Hobbs RJ, Hooper DU, Lawton JH, Sala OE, and Tilman D. 1997. Biotic control over functioning of ecosystems. Science 277: 500-504.

Chichilnisky G, and Heal G. 1998. Economic returns from the biosphere. Nature 391: 629-630.

Cleaver KM, and Schreiber GA. 1994. Reversing the Spiral: The Population, Agriculture, and Environment Nexus in Sub-Saharan Africa. Washington (DC): World Bank.

Cohen JE. 1995. How Many People Can the Earth Support? New York: Norton.

Costanza RR, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, and van den Belt M. 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253-260.

Crosson P, and Anderson JR. 1995. Demand and supply: Trends in global agriculture. Food Policy 19: 105-110.

Daily G, Dasgupta P, Bolin B, Crosson P, du Guerny J, Ehrlich P, Folke C, Jansson A-M, Jansson B-O, Kautsky N, Kinzig A, Levin S, Mäler K-G, Pinstrup-Andersen P, Siniscalco D, and Walker B. 1998. Food production, population growth, and the environment. Science 281: 1291-1292.

Daily GC, ed. 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Washington (DC): Island Press.

Dasgupta P. 1982. The Contol of Resources. Cambridge (MA): Harvard University Press.

--. 1993. An Inquiry into Well-Being and Destitution. Oxford: Clarendon Press.

--. 1995. The population problem: Theory and evidence. Journal of Economic Literature 33: 1879-1902.

--. 1998. The economics of poverty in poor countries. Scandinavian Journal of Economics 100: 41-68.

--. 1999. Economic Progress and the Idea of Social Capital. Mimeo.Faculty of Economics, University of Cambridge.

Dasgupta P, and Heal G. 1979. Economic Theory and Exhaustible Resources. Cambridge: Cambridge University Press.

Dasgupta P, and Mäler K-G. 1991. The environment and emerging development issues.1990 Annual World Bank Conference on Development Economics. Supplement to the World Bank Review and the World Bank Research Observer: 101-132.

Ehrlich PR, and Ehrlich AH. 1981. Extinction. The Causes and Consequences of the Disappearance of Species. New York: Random House.

Ehrlich PR, Ehrlich AH, and Holdren J. 1977. Ecoscience: Population, Resources and the Environment. San Francisco (CA): W.H. Freeman.

[FAO] Food and Agricultural Organization. 1996. World Food Summit Technical Document 4. Rome: FAO.

Holling CS. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4: 1-23.

--. 1986. Resilience of terrestrial ecosystems: Local surprise and global change. Pages 292-317 in Clark WC and Munn RE, eds. Sustainable Development of the Biosphere. Cambridge: Cambridge University Press.

Holling CS, Schindler DW, Walker BW, and Roughgarden J. 1995. Biodiversity in the functioning ecosystems: An ecological synthesis. Pages 44-83 in Perrings C, Mäler K-G, Folke C, Holling CS, and Jansson B-O, eds. Biodiversity Loss: Economic and Ecological Issues. Cambridge: Cambridge University Press.

Jodha NS. 1986. Common property resources and the rural poor. Economic and Political Weekly 21: 1169-1181.

Kneese A, Ayres RU, and d'Arge R. 1972. Economics and the Environment: A Materials Balance Approach. Baltimore (MD): Johns Hopkins University Press.

Koopmans TC. 1957. The price system and the allocation of resources in Koopmans TC. ed. Three Essays on the State of Economic Science. New York: McGraw Hill.

Levin SA. 1999. Fragile Dominion: Complexity and the Commons. Reading (MA): Perseus Books.

Levin SA, Barrett S, Aniyar S, Baumol W, Bliss C, Bolin B, Dasgupta P, Ehrlich P, Folke C, Gren I-M, Holling CS, Jansson A, Jansson B-O, Martin D, Maler K-G, Perrings C, and Sheshinsky E. 1998. Resilience in natural and socioeconomic systems. Environment and Developmental Economics 3: 225-236.

Lind RC, ed. 1982. Discounting for Time and Risk in Energy Planning. Baltimore (MD): Johns Hopkins University Press.

Lubchenco J. 1998. Entering the century of the environment: A new social contract with science. Science 279: 491-497.

Lubchenco J, Olson AM, Brubaker LB, Carpenter SR, Holland MM, Hubbell S, Levin SA, MacMahon JA, Matson PA, Melillo JM, Mooney HA, Peterson CH, Pulliam R, Real LA, Regal PJ, and Risser PG. 1991. The sustainable biosphere initiative: An ecological research agenda. Ecology 72: 371-412.

Mäler K-G. 1974. Environmental Economics: A Theoretical Enquiry. Baltimore (MD): Johns Hopkins University Press.

Matson PA, Parton WJ, Power AG, and Swift MJ. 1997. Agricultural intensification and ecosystem properties. Science 277: 504-509.

Mitchell RC, and Carson RT. 1989. Using Surveys to Value Public Goods: The Contingent Valuation Method. Washington (DC): Resources for the Future.

Mooney HA, Lubchenco J, Dirzo R, and Sala OE. 1995. Section 5 —Biodiversity and ecosystem functioning: Basic principles. Pages 278-325, Section 6—Ecosystem analysis. Pages 328-452 in UNEP, ed. Gobal Biodiversity Assessment. Cambridge: Cambridge University Press.

[NSB] National Science Board. 1999. Environmental Science and Engineering for the 21st Century: The Role of the National Science Foundation. Washington (DC): NSB.

Ostrom E. 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cámbridge: Cambridge University Press.

[PCAST] President's Committee of Advisors on Science and Technology. 1998. Teaming with Life: Investing in Science to Understand and use America's Limiting Capital. Washington (DC): PCAST Panel on Biodiversity and Ecosystems.

Perrings C, Mäler K-G, Folke C, Holling CS, and Jansson B-O, eds. 1995. Biodiversity Loss: Economic and Ecological Issues. Cambridge: Cambridge University Press.

Perrings C, and Walker BW. 1995. Biodiversity loss and the economics of discontinuous change in semi-arid rangelands. Pages 190-210 in Perrings C, Mäler KG, Folke C, Holling CS, and Jansson B-O, eds. Biodiversity Loss: Economic and Ecological Issues. Cambridge:

Cambridge University Press.

Pinstrup-Anderson P. 1994. World Food Trends and Future Food Security. Washington, (DC): International Food Policy Research Institute.

Portney PR, and Weyant JP, eds. 1999. Discounting and Intergenerational Equity. Washington, (DC): Resources for the Future.

Ray D. 1998. Development Economics. Princeton (NJ): Princeton University Press.

Scheffer M. 1997. The Ecology of Shallow Lake. New York: Chapman and Hall.

Simon JL. 1981. The Ultimate Resource. Princeton, (NJ): Princeton University Press.

Simon JL. 1994. Post-debate statement. Pages 195-214 in Myers. N and Simon JL, eds. Scarcity or Abundance? A Debate on the Environment. New York: W.W. Norton.

Solórzano R, de Camino R, Woodward R, Tosi J, Watson V, Vásquez A, Villalobos C, Jiménez J, Repetto R, and Cruz W. 1991. Accounts Overdue: Natural Resource Depreciation in Costa Rica. Washington, (DC): World Resources Institute and San Jose, Costa Rica: Tropical Science Center.

Solow RM. 1991. Sustainability: An Economist's Perspective. Eighteenth J. Seward Johnson Lecture in Marine Policy, June 14, 1991. Woods Hole, MA: Woods Hole Oceanographic Institution, Marine Policy Center.

[UNEP] United Nations Environment Programme. 1995. Global Biodiversity Assessment. Heywood VH, ed. Cambridge: Cambridge University Press.

Vitousek PM, Mooney HA, Lubchenco J, and Melillo JM. 1997. Human domination of Earth's ecosystem. Science 277: 494-499.

Walker BH. 1995. Rangeland ecology: Managing change in biodiversity. Pages 69-85 in Perrings C, Mäler K-G, Folke C, Holling CS, and Jansson B-O, eds. Biodiversity Conservation. Dordrecht, The Netherlands: Kluwer.

Watson RT, Dixon JA, Hamburg SP, Janetos AC, and Moss RH. 1998. Protecting our planet, securing our future: Linkages among globalenvironmental issues and human needs. Washington, DC: United Nations Environment Program, U.S. National Aeronautics and Space Administration, and The World Bank.

Wilson EO. 1992. The Diversity of Life. London: The Penguin Press.

World Bank. 1992. World Development Report. New York: Oxford University Press.