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Integrating The Environment And The Economy: Proceedings Of June 1994 Association Of Environmental And Resource Economists Workshop

Integrating the Environment and the Economy: Sustainable Development and Economic/Ecological Modelling

1994 Association of Environmental and Resource Economists Workshop

Boulder, Colorado
June 5-6, 1994

PREFACE

The 1994 AERE Workshop was held June 5th and 6th in Boulder, Colorado. The topic was **Integrating the Environment and the Economy: Sustainable Development and Economic/Ecological Modelling.** Keynote addresses were given by John Hartwick of Queens University and Michael Toman from Resources for the Future. Michael's talk was entitled "Neoclassical Economics and Sustainability," and was based on papers by Michael; and Michael, John Pezzy and Jeffrey Krautkraemer. John spoke on "Sustainability and Constant Consumption Paths in Open Economies with Exhaustible Resources."

Session topics included Sustainability : Some Basics; Sustainability: Extensions and Issues; Issues in Environmental Accounting; and Economic/Ecological Modelling and Ecosystem Valuation.

There were almost ninety participants, and my perception is that most found the workshop either productive, enjoyable, or both. I both enjoyed it and learned a lot. The weather was great, the hotel nice, and the food good. The presentations were great. Those of you who were not there missed all of the site-specific amenities, but can still enjoy the papers. I recommend them.

The papers by Bishop and Woodward; and Hrubovack, LeBlanc, and Eakin are revisions of the manuscripts that were presented at the AERE Workshop. Due to copyright considerations, only abstracts are included for the following papers: Pezzey; Toman, Pezzey, and Krautkraemer; Gottfried, Wear, and Lee; Silvestre; and Albers.

Neither the conference nor this EPA volume would have been possible without generous sponsors. These include the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, and the University of Colorado. Thanks also goes to the AERE Workshop committee members, Betsy David, Anne Grambsch, Mary Jo Kealy, Bob Leeworthy, Michael LeBlanc, and Kathy Segerson. Great on-site help was provided by four Ph.D. students in the Economics Department at the University of Colorado. Kate Carson, Kathleen Greer, Amanda Lee, and Charles Rossmann; each is specializing in environmental economics.

Edward Morey

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Papers presented at the 1994 Workshop Conference

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NEOCLASSICAL ECONOMIC GROWTH THEORY AND "SUSTAINABILITY"

by

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This paper is forthcoming in the *Handbook of Enviromental Economics,* edited by Daniel Bromley and published by Blackwell. The authors are grateful to Geir Asheim, Edward Barbier, Richard Howarth, David Pearce and Tom Tietenberg for helpful advice during the preparation of this paper. The paper also benefited from the assistance of Mary Elizabeth Calhoon and Kay Murphy. Pezzey's research was supported by the UK Centre for Economics and Environmental Development and the Economic and Social Research Council.

ABSTRACT

NEOCLASSICAL ECONOMIC GROWTH THEORY AND "SUSTAINABILITY"

The issue of "sustainability" figures prominently in contemporary discussions of natural resource and environmental management and economic development. However, the concept is not easily defined and is interpreted differently by economists, ecologists, philosophers, and others. Even among economists there are significant differences of interpretation. Some treat sustainability as not much more than another way of espousing economic efficiency in the management of services derived from the natural endowment. Others claim that conventional economic efficiency criteria are inadequate for addressing sustainability concerns.

Our aims in this paper are to identify the issues that seem to be most salient in formal economic analysis of sustainability, and to review economic growth theory that bears on these issues. In the latter effort we focus mostly on literature within the methodological mainstream of neoclassical economics, though the studies do not always maintain all the common assumptions of neoclassical theory. We first draw together arguments from economics, ecology and philosophy to briefly describe what seem to be the most important issues m addressing sustainability. Armed with this characterization, we then review several categories of studies related to economic advance, natural resource use, and environmental preservation over time. We include both representative-agent models and overlapping-generations models in the review. The concluding section of the paper summarizes our discussion and offers an overall assessment of the literature.

Economics and “Sustainability”: Balancing Trade-offs and Imperatives

Michael A. Toman

ABSTRACT. *The concept of ‘“sustainability” has been increasingly invoked in scholarly and public policy debates. Discussion has been hampered, however, by uncertainty and lack of uniformity in the meaning of sustainability. This paper seeks to identify some common ground among economists, ecologists, and environmental ethicists. Two issues seem salient: requirements for intergenerational equity and the definition of “social capital” to be provided to future generations. A concept of “safe minimum standard, ” which has received at least some recognition in the ecology, philosophy, and economics literatures, may provide the beginnings of a common ground for debate about sustainability. (JEL* Q2)

I. INTRODUCTION

The concept that use of natural resources, environmental services, and ecological systems somehow should be “sustainable” has become one of the most widely invoked and debated ideas in the area of resource and environmental management. It was a basic theme in the 1992 “Earth Summit,” the United Nations Conference on Environment and Development (UNCED), and in the World Bank’s 1992 World Development Report on environment and development. It is an issue discussed not just in professional journals but also in newspaper articles and in basic textbooks (see, e.g., Pearce and Turner 1990 and Tietenberg 1992). It is a principle behind the founding of a professional organization, the International Society for Ecological Economics, many of whose members question the sufficiency or even the validity of conventional economic approaches to resource and environmental management problems.

Despite the frequency with which the term is invoked, the concept of sustainability y remains surprisingly ambiguous. It is clear from examining various usages of the term that writers have very different meanings in mind.[1] For example, the use of the term in the 1992 *World Development Report* seems to refer primarily to the application of existing neoclassical principles of efficient resource and environmental management in developing countries. This is very different than the ideas expressed by Herman Daly (see, e.g., Daly 1990, 1991), who argues that use (“throughput”) of energy and materials must be sharply curtailed to avoid ecological catastrophe. Sustainability also is interpreted very differently by many economists, who see the natural environment as one of many fungible assets that can be deployed in satisfying human demands, and by many ecologists and ethicists, who express ‘greater concern for both ecological integrity and the interests of future generations (compare Ehrlich 1989 and Solow 1993a, 1993b, for example).

The goal of this paper is to provide some vocabulary and grammar that may be useful for this ongoing debate among economists, ecologists, and ethicists. We begin, as do many others, with the statement about sustainability from the report of the “Brundt-

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Senior Fellow, Resources for the Future.

Earlier versions of this paper were presented at, meetings of the International Society for Ecological Economics and the American Economic Association, and at seminars at the World Bank, the Agency for International Development, and the University of Maryland. I owe a large debt to Pierre Crosson, Bryan Norton, and John Pezzey, whose insights played a substantial role in clarifying my understanding of the issues raised in the paper. I also appreciate helpful conversations with Geir Asheim, Doug Bohi, Allen Kneese, and Jeff Krautkraemer, and perceptive comments by Tom Tietenberg, Scott Gordon, Tim Brennan, arid an anonymous referee on earlier drafts.

[1] See also Pezzey (1989) and Pearce, Markandya, and Barbier (1989), who catalogue scores of sometimes vague and conflicting sustainability definitions. Dixon and Fallen (1989) discuss how sustainability has been transformed from a condition on steady-state management of specific resources to an expression of broad ecological concerns.

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Toman, Michael, “Economics and ‘Sustainability': Balancing Trade-Offs and Imperatives.” LAND ECONOMICS, Volume 70, Number 4 (November, 1994). Reprinted by permission of The University of Wisconsin Press.

land Commission," the World Commission on Environment and Development (WCED). That report described sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, 43). The threat to future generations perceived in the report arise from potentially large-scale and irreversible degradation of natural systems in the course of global economic development, particularly in poorer countries.

The Brundtland statement thus focuses attention on two issues that seem to be central themes in any conception of sustainability: the nature of the current generation's responsibility to future generations, and the degree of substitutability between "natural capital" and other forms of social capital-physical investment and investment in knowledge and institutions as embodied in human capital.[2] The next two sections of the paper examine alternative views on these two issues to show how they lead to different conceptions of sustainability. In the fourth section of the paper these alternative conceptions are related to each other through a "two-tier" model of resource management based on the idea of "safe minimum standard." The fifth and last section of the paper contains concluding remarks.

II. INTERGENERATIONAL FAIRNESS

There is an enormous literature, spanning over two millennia, on concepts of distributive justice including fairness across generations. Unfortunately, there is not yet a conception of distributive justice that commands wide intellectual support. Nevertheless, there are several points of view that have attracted considerable attention in discussions of sustainability.[3] The discussion that follows emphasizes issues of intergenerational fairness even though these issues cannot be entirely divorced from the subject of the next section, substitution possibilities among components of society's wealth endowment.

One fundamental partitioning of justice concepts separates theories based on maximization of an independently defined good (teleological theories) from theories based more on innate rights and obligations (deontological theories). A further categorization can be made based on theories that emphasize the current generation and its immediate descendants-"presentist" theories-and theories that put greater emphasis on the "further future." Yet another distinction, particularly in nonpresentist theories of justice, concerns justice concepts that emphasize individuals and more "organicist" conceptions that put greater weight on community interests.

The typical criterion of discounted intertemporal welfare maximization in applied welfare economics occupies one point in the continuum of alternative justice conceptions. This criterion not only emphasizes preference satisfaction over rights; it also is highly presentist, since with *any* positive intergenerational discount rate the welfare of individuals living one generation in the future is scarcely relevant to current decision making. Many writers have suggested that the presentist focus of the present-value (PV) criterion implies an influence of the current generation over the circumstances of its more distant descendants that seems, at least intuitively, to be ethically questionable (Kneese and

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[2] In emphasizing these themes we are placing ourselves within the anthropocentric stream of debate about sustainability, in which the needs and wants of people are central, as opposed to an "eccentric" perspective that asserts the intrinsic worth of the natural environment. We also are sidestepping, without in any way minimizing, the issue of how the state of the environment may be connected to income distribution within generations-in particular, connections between poverty and environmental degradation. See Pearce, Barbier, and Markandya (1990) and World Bank (1992) for discussion of these issues. Finally, we consider sustainability primarily in the context of resource management to meet identified human needs; as opposed to the broader "co-evolutionary" perspective discussed in Norgaard (1988), which emphasizes the mutual interactions between social actions and goals.

[3] See Pearce and Turner (1990, chap. 15) for a compact summary; Pezzey (1992) provides a wide-ranging survey of motivations for considering sustainability.

Schulze 1985; Norton 1982, 1984, 1989; Parfit 1983b; Page 1977, 1983, 1988).

The debate over the ethical implications of the PV criterion is long-standing and involves a number of considerations that often seem to be misunderstood. One basic issue in this debate is the relationship between the PV criterion and the broader concept of intergenerational economic efficiency as defined by the Pareto criterion, which requires only that it be impossible to improve the welfare of members of one generation without reducing the welfare of members of some other generation. This notion of "no waste" seems desirable in any intergenerational welfare criterion, at least to those who give some weight to the importance of individual preference satisfaction. The difficulty with the PV criterion thus is not that it requires Pareto efficiency, but rather that it puts weight on the welfare of the current generation in the social welfare function that some regard as excessive.

As Page (1977, 1988) points out, there are infinitely many intergenerational social orderings consistent with the Pareto principle that allow for different sets of intergenerational welfare weights without the "dictatorship" of the current generation embodied in the present value criterion. A number of analysts have explored other social welfare criteria that preserve the Pareto principle without imposing the preferences of the current generation on future generations.[4]

This issue has been carefully considered in a series of papers by Howarth and Norgaard (see Howarth and Norgaard 1990, 1992, 1993 and Howarth 1991a, 1991b). Using an overlapping generations framework, they argue that the problem of intergenerational equity must be viewed as a problem of ethics that is distinct from economic efficiency in the Pareto sense. They further argue that the intergenerational equity problem should be approached as one that involves a fair distribution of property rights between current and future generations. This argument is a simple but powerful intergenerational extension of a standard result in welfare economics: "The choice of distribution of income is the same as the choice of an allocation of endowments, and this in turn is equivalent to choosing a particular welfare function" (Varian 1984, 209; see also Bromley 1989). In particular, Howarth and Norgaard show that while purely "egoistic" utility concerns will motivate some savings to benefit the (short-term) future (since people live more than one period and may also have concerns for their own immediate descendants), purely egoistic savings will not in general be adequate to optimize a social welfare function that includes more altruistic concerns (e.g., the well-being of the entire next generation or individuals further into the future), Howarth's and Norgaard's arguments also have important implications for analyses of environmental valuation, discount rates, and policy design (e.g., pollution taxation), since all of these ate affected by the income distribution.

Howarth and Norgaard do not investigate the range of intergenerational social welfare functions that might plausibly be invoked in connection with intergenerational equity. In their analysis they are concerned primarily with the egalitarian "maximin" criterion discussed below as an alternative to maximizing the present value of utility streams.[5] In addition, trying to achieve intergenerational equity solely through savings that transfer endowments across

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[4] See in particular Page (1977), Pearce (1983), and Burton (1993) for discussions of intergenerational discounting. These analyses suggest that a positive discount rate to reflect the growth of the economy is compatible with a zero rate of pure time preference in the social welfare function on ethical grounds. The arguments in Sandler and Smith (1976, 1977, 1982), Bishop (1977), and Cabe (1982) indicate "that the assumption of a uniform discount rate may not be consistent with intertemporal Pareto efficiency, particularly with intertemporal public goods.

[5] Howarth (1992) derives this social welfare criterion from a more restricted maximin ethic between just parents and their children. He shows that if parental altruism extends only to the direct consumption of the next generation, there is no assurance that utility levels will be maintained or increase over time; but if the current generation is concerned about the capacity of its descendants to exercise their bequest motive as well, the result is concern about the equity of welfare across all generations.

generations may not always be effective. Randall and Farmer (1993) argue that when the two-generation analyses of Howarth and Norgaard are extended to a setting with three or more generations, a kind of Coasian result obtains: the ultimate equilibrium allocation is not that sensitive to the initial distribution of property rights. Randall and Farmer argue for an approach to sustainability based on preservation rules like the safe minimum standard discussed subsequently in this paper.

The problem of intergenerational equity has received considerable attention in the economics literature through the application of a Rawlsian (1971) "maximin" concept of intergenerational rights (see, e.g., Solow 1974, 1986 and Norton 1989, as well as the work by Howarth and Norgaard cited above). The Rawlsian approach has been criticized as posing too harsh a tradeoff between equity and welfare maximization, since a strict application of the Rawlsian criterion leads to the outcome that all generations must be equally well (or badly) off-that is, there is no scope for the current generation to pursue improvements in future conditions. However, more recent analyses of the Rawlsian social welfare problem suggest that this trade-off need not be so harshly drawn. In particular, Asheim (1988, 1991) shows that when individual preferences include some altruistic concern for immediate descendants, but there is also a social agreement to follow a Rawlsian ethic involving concern for the indefinite future, it is possible within the context of social welfare maximization to have economic growth coupled with a requirement that future generations be no worse off than the present.

As Pezzey (1989, 1994a) points out, there are a number of alternatives to the maximin criterion for social welfare orderings that could be used to reflect intergenerational equity concerns. Pezzey (1994b) analyzes in some detail the implications of a criterion based on the maximization of the present value of per-capita utility subject to an ethical constraint that per-capita utility not decline over time. Like Asheim, Pezzey finds that this criterion allows for concern for future welfare without necessarily sacrificing all growth possibilities. A weaker version of this criterion would accord intergenerational equity (as indicated by nondeclining utility over time) some *finite* weight in the social welfare function, allowing for well-defined trade-offs between maximum present value and fairness (see, e.g., Broome 1992).

The discussion thus far has concerned mainly individualistic conceptions of what is good or right. Even the individualistic point of view gives rise to deep controversy. On the one hand, critics raise objections to the capacity of utilitarianism, or even the concept of human preferences, to adequately describe human interests (see, e.g.; Sen 1982; Parfit 1983b; Sagoff 1988; and Norton 1992).[6] Defenders of deontological theory, on the other hand, point out the difficulties in assigning rights to future generations (e.g., Broome 1991). Even those who do not necessarily espouse utilitarianism agree that there are some deep logical difficulties in assigning standing to "potential" future persons whose circumstances not only are largely unknown to the present generation but also are endogenous to the set of choices made by the current generation (see, e.g., Baier 1984; Barry 1977; Gelding 1972; Passmore 1974; and Parfit 1983a).

One approach to this problem has been the development of organicist arguments that invoke an obligation to the entire context of future human life-the species as a whole, and the ecological systems that surround it—rather than just to potential future individuals (see, e.g., Leopold 1949; Lovelock 1988; Callicott 1989; Norton

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[6] Some critics argue that the conventional approach to specifying preference orderings in economics is deficient on both empirical and moral grounds, since it does not distinguish "lower" or "higher" impulses, or "self-interest" and "community-motivatd" interests. The solution, it is argued, is some hierarchical representation of preferences. However, Brennan (1989) argues that this approach does not really solve any problems associated with conventional preference reasoning in economics; and in particular, that moral deficiencies associated with the outcomes of economic logic should be directly confronted as such, rather than attempting to reframe that logic.

1982, 1986, 1989; Page 1983, 1991; Nash 1989; Weiss 1989). This "stewardship" perspective emphasizes the safeguarding of the large-scale ecological processes that support all facets of human life, from biological survival to cultural existence. The stewardship perspective does not deny the relevance of human preferences, but it asserts the existence of larger societal concerns that members of society will feel (in varying degrees) beyond individualistic preferences.

The organicist position raises the interesting and as-yet unanswered question of whether there are important social values that simply cannot be captured in an individualistic resource valuation, no matter how broad and sophisticated the valuation methods are. The difficulty in addressing this issue is that the two perspectives are based on different fundamental axioms. The organicist position seems to avoid some of the difficulties in extending individualistic fairness concepts to intergenerational circumstances. On the other hand, a nonindividualistic perspective is a two-edged sword in that many of humankind's most cherished economic, political, and other social institutions derive fundamentally from giving high respect to individual rights. Organicism without constraints leads to supremacy of the group over the individual, a form of social order that history shows to be very dangerous and destructive. The two-tier system described subsequently in the paper seeks to provide a venue for considering the balance between individual trade-offs and social imperatives.

III. RESOURCE SUBSTITUTABILITY

Assuming one accepts some obligation to consider the well-being of future generations, what bundles of social capital should succeeding generations make available to their descendants? The answer to this question depends critically on one's assumptions regarding the degree of substitutability between the services provided by natural capital (material resources, waste absorption, other ecological functions, aesthetic and cultural values) and other forms of capital (plant, equipment; knowledge, skills, social institutions).

One view, to which many economists would be inclined, is that all resources are relatively fungible sources of well-being. This view appears to be influenced heavily by a number of classic and more recent applications of aggregate growth models with natural resources. A number of familiar theorems come out of this literature. In the standard growth model without natural resource constraints, the modified Golden Rule indicates that per-capita consumption and utility will grow over time provided the economy is not already saturated with capital. Clearly, sustainability presents no challenge in this world, even with positive discounting of future utilities. The same outcome obtains with natural resources provided these resources are in some sense "augmentable"—capable of being renewed or of having damages offset by compensatory investments (for a recent exposition of this see van Geldrop and Withagen 1993). Even with exhaustible resources or some other irreversible degradation of the services provided by the natural environment (such as accumulative pollution), it is possible for consumption and welfare to grow if there is sufficient substitutability between natural resources and capital accumulation, or technical progress sufficient to offset the depletion/degradation of natural resource services (Dasgupta and Heal 1974; Solow 1974, 1986; Stiglitz 1974; Baumol 1986; Dasgupta and Mäler 1991; see also the surveys in Asheim 1989, Pezzey 1992, and Toman, Pezzey, and Krautkraemer forthcoming).

From this point of view, then, large-scale damages to ecosystems such as degradation of environmental quality, loss of species diversity, or destabilization from global warming are not intrinsically unacceptable. The question is whether compensatory investments for future generations in other forms of capital are feasible and are undertaken. This is the essence of the argument advanced by Solow (1986) and Mäler (1991), based on previous work by Hartwick (1977), that investments of resource rents in other forms of capital provide the means to sustain consumption possibilities over time. Investments in human knowledge, techniques of production and social organization are especially pertinent in humankind's efforts to outrace any increases in the scarcity of services provided by the natural environment.[7]

An alternative view, embraced by many ecologists and some economists, is that such compensatory investments often are infeasible as well as ethically indefensible. Physical laws are seen as limiting the extent to which other resources can be substituted for scarce natural resources or ecological degradation. In particular, physical capital cannot be substituted for scarce energy without limit because there are minimum energy requirements for accomplishing any transformation of matter. In addition, because matter is conserved, waste is an inherent part of any economic activity; and natural limits may constrain the capacity of the environment to process these wastes.[8] Healthy ecosystems, including those that provide genetic diversity in relatively unmanaged environments, offer resilience against unexpected changes that preserve options for future generations.[9] For natural life-support systems no practical substitutes are possible, and degradation may be irreversible. In such cases (and perhaps in others as well), compensation cannot be meaningfully specified.[10]

The question of physical scale is central to this debate. If substitutability is relatively easy, then the total scale of human activity relative to the natural environment is of limited significance relative to efficient use of resources and, depending on one's ethical perspective, the adequacy of society's total savings for the future. The notion of "carrying capacity," so often invoked in sustainability debates, then would be at most ephemeral and at worst meaningless outside its traditional ecological usage. Critics of this view turn the entire argument around by claiming that physical limits cannot be ignored and then putting much more emphasis on scale issues (see, e.g., Goodland, Daly, and El Serafy 1991 and Costanza 1991).

A related issue that sometimes is overlooked is the distinction between local and global impacts when considering substitution possibilities. Local resource depletion and ecological degradation, while often having serious consequences, may be more easily compensated for by trade, economic diversification, and migration than regional

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[7] As pointed out recently by Asheim (1994) and Pezzey (1994b), Hartwick's reinvestment rule has been widely misinterpreted as an instant test of the future sustainability of an arbitrary economy. Although an economy with constant utility over time must satisfy the HartWick Rule (as Hartwick proved), observing that investment currently happens to be greater than or equal to the resource rent measured at market prices does not imply that at least the current level of utility can be maintained by imposing Hartwick's Rule from now onwards. The intuition behind this result is that an economy which is depleting its natural resources too fast for sustainability will drive resource prices and hence resource rents too low, and investment at such a level does not ensure sustainability. The correct indicator of permanent sustainability would be resource rents as measured by shadow prices which reflect the sustainability constraint (which includes the constraint of the current resource stock). This poses a challenge for those interested in developing empirical indicators of sustainable development.

[8] Concern over these issues its the economics literature has been expressed by Ayres and Kneese (1969), Kneese, Ayres, and d'Arge (1971), Ayres and Miller (1980), Perrings (1986), Anderson (1987), Barbier and Markandya (1990), Gross and Veendorp (1990), Victor (1991), Daly (1992), Townsend (1992), and Common and Perrings (1992); see also the survey in Toman, Pezzey and Krautkraemer (forthcoming).

[9] A related argument at the macro level is that environmental quality may complement capital growth as a source of economic progress, particularly for poorer countries (Pearce, Barbier, and Markandya 1990).

[10] The importance of the substitutability issue can be illustrated in connection with the debate over allocating responsibility for greenhouse gas control. If one accepts the view that investments in adaptation to climate change have limited scope for effectiveness, then the atmosphere's capacity to absorb greenhouse gases also is a depletable resource with limited substitution potential. In this case cumulative past greenhouse gas emissions can be a simple metric for assessing a fair distribution of control obligation: greater cumulative emissions by industrialized countries imply greater responsibility. However, if one sees the investment in economic productive capacity and thus in global adap tive capacity by industrial nations as having provided significant benefits that do compensate for depletion of the atmosphere's capacity for greenhouse gas absorption, then the responsibility of industrialized countries is less clear-cut.

or global adversities. On the other hand, trade distortions (e.g., discrimination against manufactured exports by developing countries) may limit national capacities to develop sustainably, and individual countries may appear to develop sustainably by "exporting" unsustainable resource use to other nations that supply materials.

The discussion in this section and the previous one suggests that, at the risk of some caricature, three alternative polar conceptions of sustainability can be identified:

1. *Neoclassical presentism*. This position does not place much emphasis on sustainability as an issue distinct from efficient resource use. The standard present value criterion is adopted for intergenerational welfare comparisons, and natural capital scarcity is assumed to be remediable (given appropriate price signals and incentives) through substitution and technical advance.
2. *Neoclassical egalitarianism*. This view is the same as (1) with respect to assumptions about managing natural capital scarcity, but it also maintains a concern about a potential shortfall in total savings for the future that is not encompassed in the present value criterion.
3. *Ecological organicism*. In contrast to (1) and (2), this view emphasizes limits on substitution between natural capital and other assets. Like (2), this view includes a concern for intergenerational fairness, but that concern is not entirely individualistic; it also encompasses concerns for ecological systems and the human species as a whole.[11]

To be sure, views on sustainability that are composites of these positions also can be defined. The model discussed in the next section allows for a continuum of views about intergenerational fairness and resource substitutability.

IV. AN EXTENDED "SAFE MINIMUM STANDARD"

In this section a simple conceptual framework is outlined that can be used in considering how individualistic resource trade-offs might be balanced against social imperatives for safeguarding against large-scale, irreversible degradation of natural capital. The framework is not intended to imply a specific decision rule. Instead, its purpose is to indicate the implications of different sustainability conceptions and to provide some common ground for consideration of differences in conceptions among economists, ecologists, and ethicists. In broad outline, the framework is a two-tier system in which standard economic trade-offs (market and nonmarket) guide resource assessment and management when the potential consequences are small and reversible, but these trade-offs increasingly are complemented or even superseded by socially determined limits for ecological preservation as the potential consequences become larger and more irreversible. The framework is an extension of the logic of safe minimum standard promulgated by Ciriacy-Wantrup (1952) and Bishop (1978). Variants of this two-tier approach have been suggested by a number of writers from different disciplines (see, e.g., Norton 1982, 1992; Page 1983, 1991; and Randall 1986).

To begin the discussion, suppose for simplicity that all potential human impacts on the natural environment can be characterized by their prospective "cost" and "irreversibility." Prospective cost can be interpreted in several ways. It can be thought of as an (individualistic) economic measure of expected opportunity cost, as an ecological measure of predicted physical impact, or as some hybrid of individualistic or organicist concerns including social values like political freedom and justice. The

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[11] It would be possible to identify a fourth position, ecological presentism, but this view could be internally contradictory and in any event it seems to hold little interest.

framework does not require a particular definition of cost, though some precision on what is counted as a cost is needed in practice when interpreting alternative conceptions of the safe minimum standard.

Similarly, irreversibility can be seen in terms of an ecological assessment of system function or as an economic construct involving the feasibility of restorative or compensating investment. Economic irreversibility here is taken to be the same as nonsubstitutability. Of course, considerable uncertainty exists regarding both the cost and irreversibility of particular human impacts. This uncertainty is in fact central to the concept of safe minimum standard.

One question that needs to be addressed is why two metrics are needed for gauging impacts and determining social responses. Economists are accustomed to valuing consequences of irreversibility in an uncertain setting (see, e.g., Krutilla 1967; Krutilla and Fisher 1985; and Fisher and Hanemann 1987), so this dimension to some extent is redundant. Indeed, the prospective cost measure could be thought of as including premiums reflecting risks that can be monetized. The concept of systemic scale in ecological research also may forge links between the severity and irreversibility of impacts (Norton and Ulanowicz 1992). This research suggests that damages to ecological systems that are larger in spatial scale or higher up in the hierarchy of natural processes—more complex, consisting of more component subsystems—is both more harmful and harder to reverse because of the complexity and slower time of adaptation in these systems.

Nevertheless, there are reasons for distinguishing the metrics. Monetizing all irreversibility suggests that compensatory investment for any environmental degradation is feasible and ethical.[12] This seems debatable, as already noted. Analytically, it rules out by assumption the ecological organicist position on sustainability defined above. To avoid this, we must retain both the cost and irreversibility dimensions.

The cost and irreversibility dimensions can be brought together in a single "sample universe" as shown in Figure 1.[13] Individuals can, in this theory, locate different impacts on the natural environment (e.g., a 5-degree global mean temperature rise or a 50 percent loss of tropical forest) in the square, depending on their own assessments of cost and irreversibility. Because of uncertainties, these assessments will reflect subjective judgments including attitudes toward known or potential risks (in other words, the cost and irreversibility assessments generally will not reflect just subjective mean or median values). Individual judgments inherently will reflect not just factual information but also personal values about the nature of the obligation to future generations. A variety of social institutions, notably the political process, education, and mass communication, presumably generate some synthesis of individual impact assessments at the societal level. The synthesis is dynamic in that it reflects a variety of forms of social learning (e.g., improvements in production technique and social organization).

We can now combine this construct with an extension of the safe minimum standard logic to indicate how individualistic tradeoffs and social imperatives regarding the natural environment might be balanced. The safe minimum standard originally was developed in the context of individual species preservation (see Bishop 1978 and Ciriacy-Wantrup 1952). The logic in this setting is that standard benefit-cost comparisons may be inadequate if the long-term cost of species loss is highly uncertain (in the Knightian sense of having probabilities that are difficult to gauge) but possibly quite substantial. Proponents of a safe minimum standard argue that with low information but high potential asymmetry in the loss function, the evenhanded assessment of benefit-cost analysis should give way to a greater presumption in favor of species

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[12] This discussion leaves aside important practical problems of measurement that arise in any approach to irreversibility.

[13] This diagrammatic approach was originally developed by Bryan Norton (see Norton 1992). The figure shown here is an adaptation of Norton's schema.

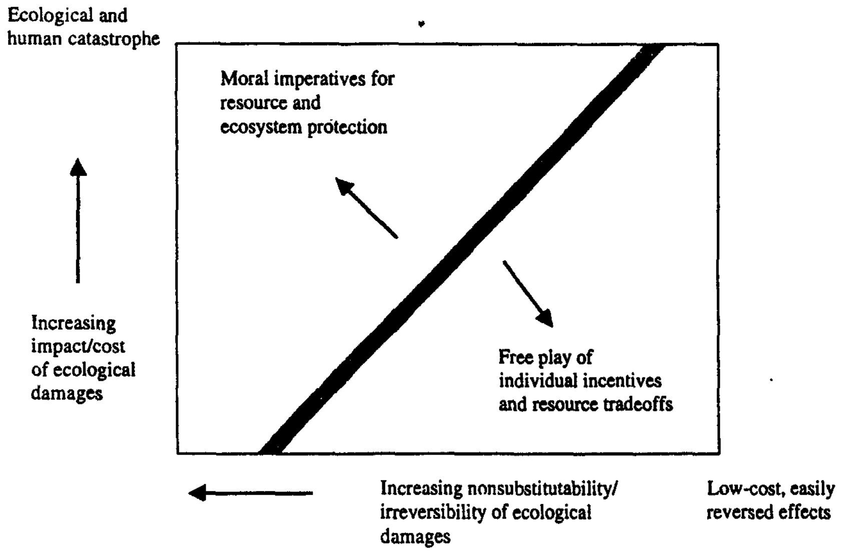

FIGURE 1

ILLUSTRATION OF THE SAFE MINIMUM STANDARD FOR BALANCING NATURAL RESOURCE TRADE-OFFS AND IMPERATIVES FOR PRESERVATION

preservation unless society judges that the cost of preservation is "intolerable."[14]

In Figure 1 we extend this logic to a continuum of potential impacts on the natural environment in the following way. First, impacts in the lower-right portion of the box involve both modest cost and a high degree of reversibility. In this area there is little threat of substantial lasting damage to the interests of future generations, and it is reasonable to rely upon individualistic valuations and trade-offs as reflected in benefit-cost analysis. Individual incentives for efficient resource use can be achieved through markets and incentive-based policies to correct "conventional" externalities.

Toward the upper-right comer of the box the costs become higher but still are relatively reversible. Here the primary concern in addition to efficient resource use might be to ensure that the current generation meets obligations to the future through general compensation for environmental degradation. On the other hand, impacts located toward the lower-left corner of the box are relatively irreversible but low in cost, so they presumably can be absorbed without too much detrimental effect on the future.

It is in considering impacts toward the upper-left comer of Figure 1 that the safe minimum standard assumes prominence. Here the long-term costs are likely to be high and substitution options likely to be low, making the impacts irreversible. Moreover, uncertainty is likely to be substantial since the impacts in question involve large-scale ecological systems and functions that remain poorly understood.

Under these conditions even individualistic, presentist valuations can provide a considerable impetus toward resource preservation. However, the logic of the safe minimum standard suggests that this impetus alone may not fully satisfy reasonable obligations to future generations, particularly when the negative effects involve

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[14] See Bishop (1979) and Smith and Krutilla (1979) as well as Castle and Berrens (1993) for further discussion of the distinction between the safe minimum standard and benefit-cost analysis. This reasoning is another way of highlighting the need for considering cost and irreversibility as distinct metrics of impact.

large-scale ecological systems and long gestation periods. One can imagine that the closer one moves to the northwest corner of the box, the more entirely individualistic valuation ciriteria are supplemented by other expressions of community interest in the form of a priori social rules of a "constitutional" nature for preserving natural capital. This is illustrated by the fuzzy demarcation line in Figure 1. Such socially determined criteria could be changed if the members of society deem the cost of preserving natural capital to be excessive, but a higher burden of proof would be placed on arguments favoring acceptance of high-cost, irreversible impacts than on acceptance of smaller impacts.

As already noted, individual perceptions of natural impacts and thus individual assessments of where the fuzzy line should be located depend strongly on individual values and knowledge. Figure 1 can be used to illustrate the different positions on sustainability summarized in the previous section of the paper. Generally speaking, ecologists with a primary concern for natural function and resilience might be more inclined than economists to emphasize the irreversibility dimension and to draw a more vertical fuzzy line, limiting even lower-cost irreversible effects; economists with greater concern for cost and more confidence in substitutability might be more inclined toward a horizontal line. Neoclassical presentists might put little or no area to the northwest of the dividing line (or even dismiss the whole construct), while ecological organicists would take a contrary view. Neoclassical egalitarians might take a middle ground, drawing a close to horizontal line but placing more area above it to limit high-cost burdens on future generations.

It should be emphasized again that there is a distinct difference between the safe minimum standard approach and the standard prescriptions of resource and environmental economics, which involve getting accurate valuations of resources in benefit-cost assessments and using economic incentives to achieve efficient allocations of resources given these valuations. Whether a resource-protection criterion is established through application of the safe minimum standard concept or entirely by trade-offs through cost-benefit analyses, that criterion can be achieved cost-effectively by using economic incentives. However, for impacts on the natural environment that are uncertain but may be large and irreversible, the safe minimum standard posits an alternative to relying just on comparisons of expected economic benefits and costs for developing resource-protection criteria.[15] It places greater emphasis on scale issues involving potential damages to the natural system than on the sacrifices experienced from curbing ecological impacts, which are seen as likely to be smaller and more readily reversible. On the other hand, the arguments in this section do not require that either the safe minimum standard as a social decision rule, or individual preferences for environmental preservation, be rigidly hierarchical. The safe minimum standard can be seen as a social compact for expressing agreed-upon moral sentiments in the face of high ecological uncertainty and potential loss asymmetry, even with egoistic consumption, bequest, and time preferences that are entirely neoclassical.[16]

The arguments in this section are somewhat similar to those developed by Vatn and Bromley (1994) regarding environmental decision making and economic valuation. Briefly, these authors argue that large-scale environmental assets or risks are inherently difficult to value meaningfully in a conventional economic sense. This is not just because of limited information about these assets and risks, which causes individual preferences to be poorly defined, but also because large-scale environmental con-

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[15] See also Pezzey (1989, 1994a), who shows with a simple example that efficient management of externalities over time may not generate sustainable welfare distributions.

[16] Tim Brennan suggests (in private communication) that the safe minimum standard also can be seen as a social decision strategy that economizes on costly information-gathering and enforcement activities relative to theoretically preferred marginal evaluations and policies.

siderations are bound up in social mores that condition individual preferences. Vatn and Bromley argue that people must be seen as dualistic, behaving as citizens as well as consumers, and that many social institutions for environmental management—including the norms surrounding government of the environment—must be seen as ways that societies have attempted to circumvent the informational and "contextual" problems surrounding individualistic valuation. This point of view justifies in particular the imposition of safe minimum standards determined through political discourse and other complex social processes.

V. CONCLUDING REMARKS

Sustainability ultimately is intimately wrapped up with human values and institutions, not just ecological functions. An entirely ecological definition of sustainability is inadequate; guidance for social decision making also is required. It must be recognized that human behavior and social decision processes are complex, just as ecological processes are. At the same time, economic analysis without adequate ecological underpinnings also can be misleading. The sustainability debate also should remind economists to carefully distinguish between efficient allocations of resources—the standard focus of economic theory-and socially optimal allocations that may reflect other intergenerational (as well as intragenerational) equity concerns:

The tension between ecological and economic perspectives on sustainability suggests several ways in which both economists and ecologists could adapt their research emphases and methodologies to make the best use of interdisciplinary contributions. For ecologists, the challenges include providing information on ecological conditions in a form that could be used in economic assessment.[17] Ecologists also must recognize the importance of human behavior, particularly behavior in response to economic incentives-a factor often given short shrift in ecological impact analyses. Economists for their part could expand analyses of resource values to consider the function and value of ecological systems as a whole, making greater use of ecological information in the process. Both methodological research and case studies are needed to synthesize ecological and economic perspectives. Research by economists and other social scientists (psychologists and anthropologists) also could help to improve understanding of how future generations might value different attributes of natural environments.

From the standpoint of economic theory, an important direction for further research is the consideration of how both physical limits and ethical' constraints on resource use may affect the time paths and shadow values of natural capital stocks, relative to the results found in standard theory. The literature on economic growth with natural resources is beginning to address these issues, and there is a lot of basic methodology that can be exploited for this purpose.[18]

One example is the work by Asheim (1988, 1991) and Pezzey (1989, 1994a, 1994b) alluded to earlier. Asheim shows that if we accept the idea of two-tiered social preferences, in which individuals have limited altruism for the next generation but also subscribe to a broader conception of intergenerational social justice, socially preferred outcomes can promote justice without sacrificing growth. In particular, this argument provides a more basic justification for the criterion of nondecreasing utility assumed in Pezzey's sustainability analysis.[19]

Another set of examples concerns the issue of resource substitution. A number of

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[17] Carpenter (1992) argues that the current state of biophysical measurement for assessing the sustainability of human impacts on ecological systems is too weak to effectively operationalize the concept of natural capital; only gross unsustainability can be detected.

[18] For further discussion see Toman, Pezzey, and Krautkraemer (forthcoming).

[19] Because of the obvious importance of uncertainty in dealing with long-term environmental change, for a complete analysis it is necessary to explicitly reflect this uncertainty in social welfare orderings. This issue is tackled in Asheim and Brekke (1993).

papers have explored the consequences for present-value-maximizing paths of including stocks in utility functions as a reflection of some sort of' "amenity" value (see, e.g., Krautkraemer 1985, 1988 and Tahvonen and Kuuluvainen 1993). In these analyses, preservation of some positive level of environmental attribute is not assured; achieving preservation in the steady state requires some combination of large initial capital accumulation and unbounded disutility from environmental degradation. Barbier and Markandya (1990), in particular, consider the consequences of requiring a threshold level of environmental preservation to stave off irreversible environmental disaster. Common and Perrings (1992) go further in discussing the basic differences between economic and ecological sustainability, and the difficulties in bringing these ideas together in a single model.

Despite its continued abuse as a buzzword in policy debates, the concept of sustainability is becoming better established as a consequence of studies in economics, ecology, philosophy, and other disciplines. With a better understanding of the interdisciplinary theoretical issues, and a better empirical understanding of both ecological conditions and social values, sustainability also can evolve to the point of offering more concrete guidance for social policy.

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Sustainability and Constant Consumption Paths in Open Economies with Exhaustible Resources

Abstract

We review some of the historical background to the capital theory approach to sustainability. We then turn to sustainability in a group of countries trading flows from an exhaustible resource. We derive an adjusted invest-resource-rents rule which leaves each country, in a group of trading countries, on a constant consumption path. Oil importers invest a fraction (greater than unity) of the rents ascribable to the current use of their own oil stocks and oil exporters invest a fraction (less than unity) of the rents ascribable to their current use of their own oil stocks. Each country's value of imports equals its value of exports. In a partial equilibrium model of a small open oil exporting country, we observe that the exact invest-resource-rents does leave the country's consumption constant over time.

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Sustainability and Constant Consumption Paths in Open Economies with Exhaustible Resources

Introduction

Since there are at least three good surveys of theoretical aspects of sustainability (namely, Solow [1991], Hammond [1994], Pezzey and Toman [1994]) available, I will not attempt a cannibalized fourth. Instead I will make some brief general remarks about the background of theory of sustainability and then turn to an area of current research, namely open economy aspects of sustainability. With this approach I can still present the references to the literature which I know about, an invaluable part of a good survey, and also introduce a reader to the core of the theory because I need this material as the stalk to graft on my open economy analysis.

There are at least three distinct ideas tied up in the economic theory of sustainability which I am dealing with today. There is first the idea that if exhaustible resource stocks are depleted today in the course of producing final goods, one need not immediately contemplate a permanent shrinkage in future production possibilities because producible or machine capital can be “over-accumulated” in order to “compensate” for the current reduction in the stock of natural capital. This idea is mentioned in Pigou [1935] and in Hayek [1941; p.88]. An important variant of this idea is of “over-accumulating" knowledge capital in order to “balance-off” the current diminution of the stock of natural capital (Robson [1980]). More generally, technical progress may allow smaller and smaller flows from exhaustible resources to maintain say a non-shrinking set of production possibilities (as in for example Stiglitz [1974]). The second idea that comes to mind is that sustainability suggests non-shrinking production possibilities as time passes. A simple indicator of non-shrinking production possibilities is of course the observed aggregate consumption level not declining over time.[1] For the case of multiple consumption goods one turns to THE utility of the current consumption vector not declining over time. Rawls maximin criterion, a moral injunction, is a polar case in this line of thought. and in part inspired the classic Solow [1974] paper on sustainability. The injunction is of course: do for others who will . occupy period t+1 what we would have preferred back in t-1, what others who occupied period t-1 would do for us, the occupants of period t. The third idea involves linking the first two ideas together. The simplest variant is of course: consume at a level which results in no shrinking of one's "capital". For an individual, this is not too difficult to contemplate since everything can be measured in dollars but at the level of the nation satisfactory measures of what "capital" is being maintained intact are generally elusive. Hicks [1942] and Pigou [1941] debated aspects of the meaning of "maintaining capital intact". This was a final exchange in the long-running debate on the links between capital and national accounting, a debate in which Pigou and Hayek sparred "and Hicks assisted in clarifying matters. A primary legacy was Hicks' [1939; Chapt. 13] notion that INCOME be defined as POTENTIAL CONSUMPTION which if "withdrawn" from current production leaves capital intact.[2] In Solow [1974], the problem of measuring "capital intact" was reduced to, given oil stocks being run down in accord with the Hotelling efficiency condition, and given the level of consumption unchanging, how much K is currently needed to "support" this program, at least for another period. This is in fact one kind of investment balancing off

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[1] Asheim [1988] [1991] has axiomitized the concept of non-declining U(C) in an economy with exhaustible resources. There is no simple way to rank two distinct efficient candidate paths. See also Pezzey [1993].

[2] This leads to the idea that Net National Product be defined as some sort of "interest" on "national wealth" (Samuelson [1961], Weitzman [1976], Kemp and Long [1982], Lozada [1992], Asheim [1994] and Hartwick [1994]).

disinvestment in another stock. Dixit, Hammond, Hoel [1980] have labelled such paths as those with “zero net investment”. Such paths are not in general those in which aggregate capital value (national wealth) are remaining constant because zero net investment is essentially changes in quantities of stocks at prevailing prices and changes in national wealth comprise both quantity changes and price changes - a chain rule calculation. The constant consumption model of Solow [1974] is of course a zero net investment model but it is not a constant wealth model. It is an increasing national wealth model. More on this below.[3]

When the stock of natural capital is regenerating itself as with say fish stocks, forest stocks, and environmental capital stocks, the notion of preserving capital intact is straight-forward in the steady state. In fact, the term sustainable yield has been around in the economics of the fishery and forestry much longer than it has been in the discussion of how any economy is performing (as in, for example, the Brundtland Report). There remains however the question of what course of action to take along the approach to the steady state (the transient trajectory) with renewable resources in the economy. If one is wedded to a constant consumption path over ail time, then the investing of resource rents is the appropriate strategy off the steady state trajectory (Hartwick [1978], Becker [1982] Hamilton [1994]). This result contains the not-new suggestion that the exhaustible resource use problem is a special case of the renewable resource use problem in the sense that in the former, the economy has only a transient path to occupy. We now turn to some detailed analysis on constant consumption paths in open economies.

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[3] I am indebted to Geir Asheim for clarifying this in conversation.

Open Economy Considerations

Consider splitting a closed economy with exhaustible resources, enjoying constant consumption over time, into two countries, one importing some oil (the exhaustible resource) from the other. We observe below that if each country saves exactly the resource rents ascribable to load resource stock flows, the importer's consumption level will be declining and the exporter's will be increasing (Asheim [1986]). We can describe this as the importer under-saving and the exporter over-saving relative to levels for constant consumption paths. Below, we characterize adjustment weights on each country's own resource rents which "neutralizes" the importer's under-saving and the exporter's over-saving. With "corrected" local savings levels, each country "ends up" on a constant consumption path, an intergenerational equity path (Solow [1974]).

The under and over saving takes the form of price changes on oil trade flows - opposite in sign but equal for each country. The adjustment weights on local own resource rents appear in offsets to these "capital gains" terms and one characterization is as an r percent rule on certain oil flows, not values. r is the rate of return, equal to the marginal product of capital in our model. We will work with an almost symmetric split of the one world into two countries. This makes the exposition straightforward and allows us to detour around special cases with corner solutions. The reader can easily develop the analysis for not nearly symmetric splits of the one world and for more than two countries. We comment on this in detail.

Under exact investment of resource rents, each country's change in consumption turns out to equal the exhaustible resource flow traded multiplied by its current price change. Thus the consumption shifts in each country can be interpreted as an adverse terms of trade shift for oil importers and a favorable terms of trade shift for oil exporters. This becomes clear when we set out a model of an oil exporting nation facing constant world prices and interest rates, at the end. No terms of trade effects or consumption “wedges” are observed under the exact invest resource rents strategy. Thus “over-saving” and “under-saving” under exact savings of own oil use rents in the two country model are a consequence of endogenous terms of trade shifts, induced, of course, via oil price changes. The oil price changes are a consequence of asset equilibrium in the market for oil stocks (Hotelling’s Rule). Our partial equilibrium model at the end has constant world oil prices; the r percent changes in resource rents operate via endogenous extraction cost shifts.

The Model

We look first at the structure of a closed one world economy. It has $S(t)$ tons of say oil left at date t. $- S(t) = R(t)$ will be used in production of $Q(t)$ equal to $F(K(t), R(t))$ at date t. $K(t)$ is non-depreciating machine capital. $F(*)$ is homogeneous of degree 1 in inputs and $K(t)$ and $R(t)$ are smoothly substitutable. $F(*)$ is concave in its arguments. (Existence of constant consumption paths over infinite time requires $F(*)$ to be Cobb-Douglas (see Solow [1974], Dasgupta and Mitra [1983] and Hamilton [1993]).) Population N, constant, only consumes.[4] We postulate the savings-investment rule (invest resource rents):

$$\dot{K}(t) = \lambda(t)R(t)F_R(t) \tag{1}$$

where $\lambda(t)$ moves exogenously through time, say near unity. $F_R(t)$ is the derivative $\partial F(\ )/\partial R$. We

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[4] This is not an issue with a Cobb-Douglas production function but otherwise, putting N, a constant in the production function can introduce complicated scale effects as the economy’s level of aggregate output, Q(t), changes over time.

also take dynamic efficiency in exhaustible resource use as given, that is (Hotelling r% Rule):

$$\frac{\dot{F}_R(t)}{F_R(t)} = F_K(t). \qquad (2)$$

Current consumption C(t) is given by C(t) = F(*) - K. If one differentiates this expression with respect to time, and does the same for (1), and one uses (1) and (2), one obtains (see the Appendix):

$$\dot{C}(t) = \frac{\bullet}{(1-\lambda(t))R(t)} F_R(t). \qquad (3)$$

The central case of investing exactly exhaustible resource rents (namely $\lambda = 1$) yields C = 0 Hartwick [1977]. See also extensions[5] in Dixit, Hammond, Hoel [1980] and cairns [1986].).

Consider the value of aggregate capital or national wealth W(t) in this economy at date t. We define $W(t) = K(t) + S(t)F_R(t).$ Observe that $W(t) = \dot{K}(t) + S(t)\dot{F}_R(t) + F_R(t)\dot{S}(t)$ and W(t) is the change in wealth (aggregate capital value) in the economy at date t. The following result can be derived. If the economy is efficient, has net investment zero, and has constant returns to scale in F(K,R) then

$$C + \dot{W}(t) = W(t)F_K(t)$$

or C + W(t) is the interest flow from current wealth W(t). The demonstration requires simple substitution, i.e. $C = F(\cdot)-\dot{K},\ F(\cdot) = KF_K + RF_R,\ \dot{K} = RF_R,$ etc. This result is quite Hicksian since the income flow on the left is interest on capital on the right. The "logic" of Hicks' position suggests that the left hand side is net national product in this economy. Asheim [1994] 1994a seems to espouse this view. W(t) includes capital gains $S(t)\dot{F}_R(t)$ on oil stocks and these terms

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[5] These include extending consumption C to a vector in U(C). Then U(C) remains constant and extending our two capital goods K and S to many capital goods. The C=0 result was proved as an if and only if theorem. Our investing resource rents can be interpreted as aggregate or combined investment being zero. Another extension was to treat this combined investment as positive and constant.

have not been included in NNP in the modem stream of thought in national accounting, although some observers recommend land revaluations be placed in NNP (see Hartwick [1992] and references there). It turns out that these identical capital gains are in the WF_K term on the right. This suggests taht there is a more basic relation lying within ours above (it is $C - KF_K$) and that the claims for $C + W(t)$, with its capital gains on current oil stocks, as the ‘formula” for NNP suspect. We end this discussion with the observation that $W(t)$ above is not constant for the Solow [1974] constant consumption, zero net investment model. Thus maintaining capital value constant (capital “intact”?) is a separate matter from maintaining consumption constant over time or maintaining aggregate investment zero over time.

We now split the one world economy $(\lambda = 1)$ into two price-taking, trading countries We set $K_1(t) = K_2(t)$, given $K_1(t) + K_2(t) = K(t)$ above. We set $N_1 = N_2$ with $N_1, + N_2 = N$, above. We make country 1 (C1) less endowed with oil stocks, that is $S_1(t) < S_2(t)$ with $S_1 + S_2 = S(t)$, above. We assume $S_1(t) \cong S_2(t)$ so that country 1 will import $\in(t)$ a small amount of $R(t)$ at each date. Since $K_1 = K_2$, efficiency requires that $R_1(t) + \in(t) = R_2(t)$ where $R_i(t)$ is use of exhaustible resource from stock $S_i(t)$. World prices are given from the one large country scenario earlier.

(a) The oil importer (C1)

We have the output balance

$$C_1(t) = F(K_1(t), R_1(t) + \in(t)) - \dot{K}_1(t) - \in F_{R_1}(t) \tag{4}$$

where $\in F_R(t)$ is payment for oil imports, $\in(t)$, and $K_1(t)$ is own investment in $K_1(t)$. In keeping with each country “covering off" the economic depreciation of its own oil stock $S_i(t)$, we have

$$K_1(t) = \lambda_1(t)\ R_1(t)\ F_R(t) \qquad (5)$$

where $\lambda_1(t)$ is a fraction, endogenous and presumably near unity for $\in(t)$, small. Our task is to characterize $\lambda_1(t)$ since (5) represents the "adjusted" invest resource rents rule. We also have $\dot{F}_{R_1}/F_{R_1} = F_{K_1}$. These derivatives will be the spree as those in (2). If one differentiates (4) and (5) with respect to time and combines them, and uses (5) and (2), one obtains (see the procedure in the Appendix):

$$\dot{C}_1(t) = \frac{\bullet}{(1-\lambda_1(t))R_1(t)}\ F_R(t) - \in(t)\dot{F}_R(t). \qquad (6)$$

It follows that $\dot{C}_1(t) = 0$ if

$$\frac{\dot{\Delta}_1(R_1)}{\in(t)} = F_K(t), \qquad (7)$$

where $\dot{\Delta}_1(R_1) \equiv \overset{\bullet}{\overline{(1-\lambda_1)R_1(t)}}$ . . (Recall that $F_R/F_R = F_K$.) This condition for $C_1 = 0$ is an r percent rule in quantities, since $F_K(t)$ is the "rate of interest" here and $\in(t)$ and $(1-\lambda_1(t))\ R_1(t)$ are quantities of oil. This r percent rule defines the time path of $\lambda_1(t)$ and when combined with (4) becomes the adjusted invest resource rents rule.[6] Observe that if $\lambda_1(t) = 1$, then we would have the unadjusted invest resource rents rule and (6) would become

$$\dot{C}_1 = -\in(t)\dot{F}_R(t).$$

This is a rendering of the result in Asheim [1986], namely, if country i invests its resource rents, its $C_i(t)$ will not be constant. In this case, importers C1's $C_1(t)$ is declining because it is "under-saving" in revering its own economic depreciation in its stock $S_1(t)$ and in paying for imports, $\in(t)$. Thus $\lambda_1(0)$ must be greater than 1 and decrease toward 1 as time passes.

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[6] Asheim [1986] and Asheim [1994a] contain expressions for country i's savings to cause C_i to remain constant. Their appearance and derivation are quite different from our adjusted resource rents expressions yielding $C_i = 0$.

Observe that $\in(t)F_R(t)$ is a quantity traded $\in(t)$ multiplied by a price change $F_R(t)$ and is thus a terms-of-trade effect. $\in(t)F_R(t)$ equals $\in(t)F_R(t)F_K(t)$. Hence the current decline of $C_1(t)$ from $C_1(0)$, given $\lambda_1(t)$ set at 1 is $\int_0^t \in(t)F_R(s)F_K(s)ds$ where $C_1(0)$ is a constant of integration. Since $\in(t) = -\dot{S}_\in(t)$ where $\dot{S}_\in(t)$ is the decline in C2's stock resulting from exporting $\in(t)$, we have[7]

$$C_1(0) - C_1(t) = - \int_0^t \dot{S}_\in(s)F_R(s)F_K(s)ds.$$

Wealth in C1 at date t is $W_1(t) = K_1(t) + S_1(t)F_R(t)$ and $W(t) = K_1(t) + S_1(t)F_R + S_1(t)F_R$. Given $C_1 = F(K_1,R_1) - K_1 - \in F_R,K_1, = \lambda_1R_1F_R,$ constant returns to scale in $F(\cdot)$, and efficiency, one gets $C_1 + W_1(t) = W_1(t)F_K(t)$ or $C_1 + W(t)$ is interest on own wealth. This balance relation simplifes to $C_1 = K_1F_K + (1-\lambda_1(t))R_1F_R$. This contrasts with the closed economy analogue in which C equalled KF_K alone. Thus $(\lambda_1(t) - 1)R_1F_R$ is income “withdrawn” from K_1F_K to pay for the oil imports in C_1. The constant C_1 is less than interest on local K. The capital gains on oil stocks $S_1(t)F_R(t)$ in W_1 again cancel with such gains in $W_1(t)F_K$ and this suggests that $C_1 + W_1(t)$ is not a satisfactory “formula” for NNP in this economy. More on defining NNP below.

(b) The oil exporter (C2)

C2'S situation is the mirror image of that of the oil importer. Now C2's savings to replace her current oil use are $\lambda_2(t)R_2F_R(t)$, where $R_2(t)$ is current oil extracted in C2. $R_2(t)$ -

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[7] The term $-\int_0^t \dot{S}(s)F_R(s)ds$ figured prominently in Hartwick [1994]. It was a key measure of wealth. The analogous expression for machine capital was also prominent. See also Solow [1986]. Here we are dealing with a gap between two flows, $C_1(0)$ and Cl(t), not stocks. Hence the appearance of $F_K(s)$ under the integral.

$\in$ (t) is used in production in C2. Hence C2's replacement rule is

$$\dot{K}_2(t) = \lambda_2(t)R_2(t)F_R(t). \tag{8}$$

C2's value balance relation is

$$C_2(t) = F(K_2(t), R_2(t) - \in(t)) - \lambda_2(t)R_2(t)F_R(t) + \in(t)F_R(t). \tag{9}$$

We now differential (8) and (9) with respect to time, combine them, use (8) and (2) and obtain (see the procedure in the Appendix):

$$\dot{C}_2(t) = \frac{\bullet}{(1-\lambda_2(t))R_2(t)} F_R(t) + \in(t)\dot{F}_R(t). \tag{10}$$

This is the same as (6) with a sign change. (10) yields our principal savings rule result, now for C2, namely $C_2(t) = 0$ if

$$\frac{\dot{\Delta}_2(R_2)}{\in(t)} = F_K(t) \tag{11}$$

where $\dot{\Delta}_2(R_2) \equiv -\frac{\bullet}{(1-\lambda_2(t))R_2(t)}$. (11) characterizes the time path of $\lambda_2(t)$ in the investment rule in (8). The rule is the same as that for C1 in (7) except in our case $\lambda_2(t)$ will be less than unity, and will increase toward unity as time passes. ($\lambda_1(t)$ was above unity and declined toward unity as time passed.)

For $\lambda_2(t)$ set equal to 1.0, $C_2(t) > 0$ by current capital gains $\in(t)F_R(t)$. C2 is in fact over-saving relative to a constant consumption scenario, and for this case

$$\begin{aligned} C_2(t) - C_2(0) &= \int_0^t \in(s)\dot{F}_R(s)ds \\ &= -\int_0^t \dot{S}_{\in}(s)F_R(s)F_K(s)ds. \end{aligned}$$

Our crucial adjustment terms $\lambda_1(t)$ and $\lambda_2(t)$ are, in view of (7) and (11), not independent.

(7) and (11) imply

$$\dot{\Delta}_2(R_2) - \dot{\Delta}_1(R_1) = 0. \tag{12}$$

(12) indicates, roughly speaking, that for the case $\lambda_1 = \lambda_2 = 1$, C1's under-saving matches C2's over-saving. $\lambda_1(t)$ and $\lambda_2(t)$ ($\neq 1$) in (12) reflect this balancedness of the adjustments for over- and under-saving between our two countries. In fact $\lambda_1(t) -1 = 1- \lambda_2(t)$ because $k_1(t) + K_2(t) = K(t)$ where $k(t)$ is investment in the closed economy case and $R_1(t) + R_2(t) = R(t)$.

Again for C2's wealth defined in $W_2(t) = K_2(t) + S_2(t)F_R(t)$ we can obtain $C_2 + W_2(t) = W_2(t)F_R(t)$, i.e. the left hand side is interest on local wealth. Again capital gains on oil stocks cancel on both sides to leave $C_2(t) = K_2(t)F_K(t) + (1-\lambda_2(t))R_2(t)F_R(t)$. The oil exporter enjoys a constant level of consumption above the income from interest on $K_2(t)$ because it receives extra income from exporting oil. (Note that $(1-\lambda_2(t))$ is positive.)

Corner Solutions and More than Two Countries

We have characterized the savings-investment rule which yields constant consumption paths for our two-country, trading world with an essential exhaustible resource. It is an adjusted invest-resource-rents rule. Our framework was two almost identical countries. This made trade flows small so that neither country was specialized and the two country assumption allowed us to sign the oil flows from exporter to importer. Clearly no part of our calculations depended on our assumption of $K_1 = K_2$ and $S_1 \cong S_2$ with $S_1 < S_2$. Suppose, however, that C2 owned all the oil. In this case R_1F_R is zero and weigting this by λ_1 does not yield more saving. (An approach for this case is for C2 to have $\lambda_2(t) = 1$ and to transfer $\in(t)F_R(t)$ to C1 in order to have $C_1 = C_2 = 0$. This was proposed by Asheim [1986].) However, as long as own oil use

$R_1(t)$ is infinitesimally positive, $\lambda_1 R_1 F_R$ (= K_1) can be defied and our two-country results go through. (We require $C_1(t)$ and $\lambda_1(t)$ to remain positive.) Thus as long as each country holds' some positive stock $S_i(t)$ at t, our adjusted saving-investment rule is relevant. (We require that each country owns sufficient capital K to have income to pay for imports of oil in order to rule. out comer solutions.)

With say three countries, the pattern of oil flows in trade becomes more complicated. Suppose C1 is an oil importer and C2 and C3 are potential exporters, being equally 'over" endowed with oil stocks. Suppose $K_1(0) = K_2(0) = K_3(0)$. In this case C1 should import equal amounts from both C2 and C3. It is not complicated to use our above reasoning to obtain appropriate $\lambda_1(t)$, $\lambda_2(t)$ and $\lambda_3(t)$ for this case. Our $\lambda(t)$ adjustment factors "work" for the many-country case. Note, also, that standard national accounting procedures "work" for each country in the trading system. In particular the value of exports equals the value of imports for each country. Also domestic NNP in each nation equals consumption $C_i(t)$ plus domestically financed investment. That is, $C_i(t) + \lambda_i(t)R_i(t)F_R(t) + X_i(t) - M_i(t)$ is $NNP_i(t)$ for country i, where $\lambda_i(t)R_i(t)F_R(t)$ is investment in i generated from current domestic production, $X_i(t)$ is current exports and $M_i(t)$ is current imports. All components are denominated in the numeraire commodity price, namely final goods output $X_i(t) - M_i(t)$ equals zero in our framework. In the two country "example", $M_1(t)$ were oil imports and $F_1(\cdot) - C_1(t) - \lambda_1(t)R_1(t)F_R(t)$ were exports of the final good. This yields $NNP_1(t)$ in value-added in C1 as $F_1(\cdot) - M_1(t)$. Note that $F_1(K_1, R_1 + \epsilon)$ here is gross of oil import flow ϵ. Hence $F_1(\cdot) - \epsilon F_R(t)$ is C1's valued-added derived from domestic factors of production. Hence $F_1(\cdot) - M_1(t)$ is domestic valued-added and equals C1's NNP(t).

In C2, $NNP_2(t) = C_2(t) + \lambda_2(t)R_2(t)F_R(t) + X_2(t) - M_2(t)$. Given $C_2(t)$ in (9), it follows that $NNP_2(t) = F_2(K_2,R_2- \in) + X_2-M_2$ is value-added and $X_2-M_2 = 0$. In each country, the value” of exports equals the value of imports in “free trade”. World NNP equals $NNP_1(t) + NNP_2(t)$ which in turn equals world value-added $F(K,R) \equiv F(K_1+K_2,\ R_1+R_2) = F_1(K_1,R_1+\in) + F_2(K_2,R_2 - \in)$.

An Oil Exporter Facing Constant Prices and Interest Rates

Our analysis above involved two country trade with endogenous prices, including the marginal product of capital, the interest rate. These prices were changing over time. Consider the case of a price-taking “oil republic” (OR) a country living off exports of oil. This is an autonomous problem. World oil prices will be constant at p per ton and the OR will have unchanging extraction costs. e(R) for R tons currently extracted from its stock, S(t). We assume $e(0) = 0$ and $e_R \equiv de/dR > 0$ and $e_{RR} \equiv d^2e/dR^2 > 0$. There is a constant population (say just consuming so that e(R) has no labor costs in it) and extraction is pursued to maximize discounted net profit. Hence

$$\frac{\dot{\overline{p-e_R(R)}}}{p-e_R(R)} = r \tag{13}$$

is satisfied (the Hotelling r% efficiency rule). r is the constant discount (interest) rate. We assume that the elders in this OR invest $R(t)\cdot [p-e_R(t)]$ abroad each period and live off current interest income $rH(t)$ plus current producer surplus $L(t) = pR(t) - e(R(t)) - R(t)\text{-}[p-e_R(t)]$. That is consumption

$$C(t) = rH(t) + L(t). \tag{14}$$

Since interest rH(t) is being drawn off wealth abroad period by period, we have $H(t) = \int_0^t [p-e_R(s)]R(s)ds + H(0)$. Thus[8] $\dot{H}(t) = [p-e_R(t)]R(t)$. If one differentiates (14) with respect to time and uses (13) and $H = [p-e_R]R$, one obtains C(t) = 0. Hence investing oil rents abroad and living off the current interest on such, plus current producer surplus, yields a constant consumption path.[9] When S(t) declines to zero at say T, there will be H(T) dollars invested abroad and C(T) will equal rH(T) which will be the same value as was being enjoyed up to T. Clearly this policy of efficiently extracting oil and accumulating rent, net of interest, abroad is a savings-consumption strategy identical with selling off S_0 at market price $V(S_0) = \int_0^T [pR^*(t) - e(R^*(t))]e^{-rt}dt$ at $t=0$ and setting $C(t) = rV(S_0)$. (*'s indicate optimal values.) This is true because there are no market imperfections or uncertainties in our set-up, and the problem is autonomous.

Our autonomous, constant price and interest rate model for a single oil exporter differs from that for exporter C2 in our two country model in the sense that oil prices heed by C2 varied over time and generated terms of trade changes in $\in(t)\dot{F}_R(t)$. We had to "neutralize" these capital gains enjoyed by C2 with an adjusted invest resource rents savings rule. The constant oil price p eliminated capital gains in our autonomous model of the OR. In both models agents were acting with perfect foresight so that they could anticipate price and interest rate changes and optimize appropriately.

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[8] H(t) is another instance of the index number mentioned in footnote 1. Clearly this index number is cumulative uncompounded or discounted rent. The lack of compounding occurs here because potential interest accumulation is "neutralized" by the period by period drawing. off of current interest on the capital value.

[9] This argument was set out in detail in Hartwick and Hageman [1993] but no formal demonstration of C(t) = 0 was given.

Concluding Remarks

There are indeed subtleties in moving from a unitized world system to a system of' countries trading flows from their exhaustible resource stocks and each maintaining consumption constant over time. We derived the "wedges" that arise when our investment is financed in oil importing countries by own resource rents and derived adjustment weights for the own savings (resource rents). Oil importers should save more than resource rents ascribable to their own exhaustible resource flows and oil exporters should save less than resource rents ascribable to their own exhaustible resource case. Our subsequent model of a small open oil exporting nation, a PRICE-TAKER at a constant interest rate and commodity prices, revealed no "wedges" that were seen in the two country system with endogenous prices. Thus trade introduces subtleties to the derivation of constant consumption paths because prices are indeed moving over time and these price change effects show up as endogenous terms of trade effects. Relatively complicated savings-investment rules are needed in each country to neutralize these terms of trade effects on the simple invest-resource-rents rule, familiar for closed economies.

With our adjusted savings rule, we have been able to re-construct the closed economy set-up, given multiple countries in trade. This was our goal. We also noted that no new valuation issues were met and that traditional NNP measures "go through" in the open economy system. We were also able to relate constant consumption paths to interest-on-wealth expressions. These are compelling Hicksian notions of current national "income" being interest on national wealth. However constant consumption paths are not reflections of constant wealth paths. In no case was national wealth remaining constant over time.

Appendix: Derivation of Equation (3)

One differentiates $C(t) = F(K(t),R(t)) - K(t)$ to obtain

$$C = F_K K + F_R R - K(t) \tag{A1}$$

One differentiates equation (1) to obtain

$$\dot{K}(t) = \lambda(t)R(t)\dot{F}_R(t) + \lambda(t)F_R(t)\dot{R}(t) + R(t)F_R(t)\dot{\lambda}(t). \tag{A2}$$

In A1, for F_K substitute $F_R(t)/F_R$ from (2) and $\lambda(t)R(t)F_R(t)$ for K. Also for K(t) in A1 substitute the expression in A2. A1 reduces to $C = \frac{\bullet}{(1-\lambda(t))R(t)} F_R(t),$ our expression in (3) in the text.

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THE OPTIMAL SUSTAINABLE DEPLETION OF NON-RENEWABLE RESOURCES

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Abstract. In a simple growth model based on capital accumulation, non-renewable resource depletion and constant technology, the maximum sustainable utility level is strictly less than net national welfare; and a growth path may be unsustainable, even though it has rising net wealth. PV-optimal sustainability ('opsustimality') is defined as maximising the present value of utility, subject to utility being non-declining forever. The opsustimal path will either have a finite phase of rising utility, and followed by a continuous transition to constant utility; or will always have constant utility. Only on the opsustimal path does non-declining net wealth always coincide with sustainability. Numerical simulations suggest that a rising opsustimal path has higher utility than the PV-optimal path at the same time. A consumption tax can achieve sustainability in a market economy only by approaching a 100% subsidy, and neither a resource depletion tax nor a resource stock subsidy can achieve sustainability.

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RETHINKING SUSTAINABILITY

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ABSTRACT

This paper argues that sustainability is an inappropriate guiding principle for the design of policy in a democratic setting. If policy is to be generally implementable then its design must be consistent with the social setting in which it is applied. In a democratic setting that permits individuals to act and vote in accordance with views of distributive Justice that are not necessarily consistent with sustainability, policy based on a sustainability criterion will not be generally implementable. The alternative conceptual framework I propose is based on three key elements: the relaxation of the distinction between ethics and preferences; the recasting of an intergenerational equity problem as an intragenerational allocation problem; and the requirement that Intergenerational resource allocations be intragenerationally efficient.

"The less you know about it, the better it sounds"

- Robert M. Solow (1991)

1. INTRODUCTION

This paper argues that sustainability is an inappropriate guiding principle for the design of policy in a democratic setting. This is not a fashionable stance to take. The tide of academic literature and political rhetoric seems to flow overwhelmingly in quite the opposite direction. Indeed, it is difficult to find a recent policy statement of any kind that does not make some reference to the term. The continuing absence of a clear definition of sustainability does not seem to detract from its political appeal. A cynic might even claim that the ambiguity of the notion is the main source of that appeal. It is not my intention in this paper to attempt to resolve that ambiguity by proposing yet another definition of sustainability. My primary purpose is to argue that an emphasis on sustainability in the design of policy in a democratic setting is misplaced.

The paper is organized as follows. In the next section I present a case against the imposition of a sustainability criterion. in the design of policy in a democratic setting. I then propose in section 3 an alternative approach to intergenerational resource allocation. I present a simple illustrative application of the proposed approach in section 4. Section 5 concludes the paper with a brief summary and some closing remarks.

2. RETHINKING SUSTAINABILITY

Sustainability as a societal goal is based on a particular ethical. stance. It rests on a view of distributive justice that gives at least some consideration to the well-being of future humans and/or other elements of the biosphere. Within that general class of ethical views there are many specific positions that are consistent with some notion of sustainability. They range from the purportedly non-anthropocentric view of the deep ecologists [Naess (1986)] to some form of (anthropocentric) egalitarianism embodied in a Rawlsian-type intergenerational social welfare function [Solow 1974]. It is not my intention to present a taxonomy of these ethical positions nor to debate their relative philosophical **merits.**[1] Nor do I intend to examine the nature of the link between an ethical stance and the definition of sustainability that it implies. I do not mean to imply that this is a topic unworthy of examination. Indeed, it is my impression that the clarity of the debate over competing definitions of sustainability could be enhanced if more attention was paid to the axiomatic derivation of a proposed definition from. the particular ethical position underlying **it.**[2] Consider for example the disagreement between those who define sustainability to mean the preservation of the “natural capital stock” [Pearce (1988), Costanza and Daly (1992)] and those who define it to mean the preservation of the “composite capacity to produce well-being” [Solow 1992]. This debate has sometimes confused two distinct Issues. The focus of the debate has been on the degree to which manufactured and human capital can physically substitute for natural capital in production. I believe this focus is misplaced. To the extent that there do exist at least some physical substitution possibilities, there remains the issue of whether or not it is ethically acceptable for the current generation to make those substitutions (perhaps irreversibly) without the consent of future generations. I believe this is the fundamental source of disagreement in this debate. It is a conflict of ethical positions. If one adopts an ethical position embodying an obligation to preserve for future generations the same *opportunities to choose* that were available to the current generation then one is obliged to make no irreversible substitutions. Whether or not such substitutions are physically possible is then irrelevant.[3]

Making the ethical positions that underlie various definitions of sustainability more explicit would help to clarify the differences between them but it would not necessarily lead to a convergence of those definitions. There is unlikely to arise a consensus about the precise meaning of sustainability until a consensus is reached about the meaning of distributive justice. No such consensus seems imminent. The main point I want to make in this paper is that the absence of a universally accepted notion of distributive justice has implications more fundamental than ambiguity in the precise meaning of sustainability. It raises the question of whether sustainability - no matter how it is defined - is an appropriate guiding principle for policy at all.

Disagreement over the meaning of distributive Justice can and does extend beyond the set of ethical positions that are consistent with some notion of sustainability. Some ethical positions. do not imply sustainability in any sense. Consider a deliberately extreme example. “It is perfectly just for my generation to consume the entire resources of the planet at the expense of future generations because we were here first”. I do not think there are many people who subscribe to this ethic (although I suspect there are some). The point is that this ethical position and many less extreme ethical positions are not consistent with sustainability. This means that the adoption of sustainability as a guiding principle for policy is restrictive. What is the basis for restricting the set of admissible ethics in this way? I submit that the restriction is an arbitrary one. This is not objectionable in itself. All guiding principles are fundamentally arbitrary. My objection to the restrictiveness of sustainability is based on more pragmatic grounds.

I begin with the assertion that any guiding principle for the design of policy should be consistent with the social setting in which it is to be applied. By consistent I mean here that the resource allocation implied by a policy prescription must be implementable given the social structure, in the sense that there cannot exist a constitutional mechanism by which the implementation of the allocation would be blocked. This is admittedly an arbitrary stance to take. It reflects my own view that policy should be designed with its eventual implementation squarely in mind. Not everyone may agree with this position but it seems sensible to me. My purpose is to examine what this criterion implies for the design of policy in matters of intergenerational resource allocation.

Whether or not a particular guiding principle is consistent with a given social structure will of course of depend on the nature of that structure. I will focus here on democratic structures, and do so at a fairly abstract level. I will assume a structure in which each agent is free to vote against a candidate allocation in favor of some alternative if they so wish. This is a reasonable approximation to a democratic system for the purposes of this paper. I should stress that it is not the purpose of this paper to advocate democracy over some other social structure. I focus on democracy only because it is the system currently in place in many countries.

If a guiding principle for policy is to be consistent with a democratic structure then it must be respectful of the voting rights of the members of that democracy. In the democracies with which I am familiar, voting rights are not restricted to those individuals who subscribe to an ethical position that is consistent with sustainability. Individuals are permitted to vote regardless of their ethical position, within certain limits. These limits are often enshrined in a constitution. For example, in Canada and the United States, a charter of rights and freedoms restricts the ability of the collective to violate what are deemed to be the rights of the individual. In Canada it is illegal to incite hatred of a particular social group. These restrictions reflect the fact that there are some ethical positions that these societies have deemed to be unacceptable.[4] Ethical positions that are inconsistent with some notion of sustainability may some day be included among them. Currently they are not. To impose sustainability as a guiding principle for resource allocation is to ignore in principle the voting rights of individuals who subscribe to those ethical positions. This creates the potential for the policies formulated under this guiding principle to be systematically unimplementable. This does not mean that democracy is necessarily inconsistent with sustainability. I have already noted that some notion of sustainability could possibly be enshrined in a constitution without necessarily rendering it undemocratic. Even without such a restriction, it is possible that all Individuals with voting rights might happen to subscribe to an ethical position that is consistent with sustainability. But to impose a guiding principle that does not conceptually admit a converse possibility fails my implementability criterion and is in my view inappropriate.

A conceptual framework for the analysis of intertemporal resource allocation issues must be able to accommodate conflict among individuals with voting rights if it is to be generally useful in the guidance of policy formulation. This rules out the imposition of sustainability as a guiding principle. More generally, it rules out the imposition of an intergenerational welfare function on a planning problem designed to guide policy. To do so implies that all of the agents in the modeled economy subscribe to the ethical position embodied in the welfare function. This is true regardless of whether or not the particular welfare function is consistent with sustainability. Such modeling exercises should be interpreted only as positive analyses of how an economy of agents with a common ethical position would optimally allocate resources across generations. They are inadequate for guiding policy in a realistic democratic setting because by construction they cannot in general admit differences in ethical positions.

I have argued that it is generally inappropriate to impose sustainability directly or to assume a particular intergenerational welfare function for the. purpose of guiding policy in a democracy. So how should one proceed? In the next section I propose one possible approach. I focus on the question of intergenerational equity rather than a more general consideration of distributive justice - that might Include, for example, the perceived rights of other sentient beings - only because this issue has received the most attention in the economics literature. The approach I propose could in principle be extended to encompass broader issues of distributive justice.

3. DEMOCRACY AND INTERNATIONAL RESOURCE ALLOCATION

There are three key elements of the conceptual framework I advocate for addressing issues of intergenerational resource allocation in a democratic setting. The first is the relaxation of the distinction between preferences and ethics (or "social preferences").[5] This distinction is sometimes used to justify the imposition of an intergenerational welfare function that applies positive weight to future generations in an economy in which agents have preferences defined only over their private consumption.[6] The welfare function is interpreted as a reflection of an ethical position that is conceptually distinct from preferences. This distinction may or may not be a philosophically interesting one; in any case it has little practical relevance in a democratic setting in which a vote motivated by preferences is treated equally alongside an observationally equivalent vote motivated by ethics. If a conceptual framework is to have practical relevance then it cannot rest on a distinction between ethics and preferences.

The second key element is the recasting of an intergenerational equity problem as an intragenerational allocation problem. The interests of future generations can be represented in a democratic setting only to the extent that current generation agents act as their advocates. This necessitates a focus on current generation agents. I have already argued that whether this advocacy is motivated by ethics or preferences is practically irrelevant. The important point to recognize is that this advocacy reflects some concern for the well-being of those future generations. The well-being of current generation agents can depend on the well-being of future generation agents just as surely as it depends on their own consumption. A transfer of consumption from the current generation to future generations can potentially make both generations better off. A conceptual framework that places exclusive focus on private consumption as the determinant of well-being is inappropriate. An equally important point to note is that current generation agents can differ in the degree to which they care about future generations. If these different agents are entitled to act and vote in a democratic setting then there can arise a conflict of interests among current generation agents. It is *this* conflict of interests that must be accommodated in a conceptual framework for addressing intergenerational resource allocation issues in a democratic setting. To frame these issues in terms of a conflict of interest *between* generations is not helpful for the purpose of guiding policy.

The third key element of the conceptual framework I advocate is a focus on intragenerational efficiency in the assessment of an intergenerational resource allocation. If each agent in the current generation is free to vote against a candidate intergenerational allocation in favor of some alternative, then implementability of the candidate allocation requires that it be efficient from the perspective of the current generation. If there exists an alternative allocation at which all current generation agents are better off than at the candidate allocation then the candidate allocation would be unanimously rejected in favor of the alternative. The candidate allocation cannot be implemented without a suspension of the democratic process. Intragenerational efficiency is a necessary condition for implementability in this setting.

It should be noted that intragenerational efficiency does not necessarily imply intergenerational efficiency. Suppose, for example; that current generation agents do not care at all about the well-being of future generation agents, and that there exist two allocations between which current generation agents are indifferent. If these two allocations have different implications for the well-being of future generations then imposing intragenerational efficiency alone will not guarantee intergenerational efficiency: the allocation In which the future generation is worse off will pass the intragenerational efficiency screen and could be chosen. But intergenerational efficiency is only a relevant criterion if the current generations deems it to be so, and it will be deemed so only if there are current generation agents who care about future generations. If there is at least one such agent then intergenerational efficiency is implied by intragenerational efficiency. Therefore, nothing meaningful is lost by focusing exclusively on intragenerational efficiency.

Intragenerational efficiency will generally not identify a unique social optimum. There will generally exist a continuum of efficient allocations from which one must be chosen according to some social choice rule. It should be stressed that there is nothing internally inconsistent about this. In a democratic setting the particular voting rule in place will determine which allocation is chosen and this voting rule is taken as given for the purpose of guiding implementable policy.

In the section following I present a simple illustrative example of the approach I have proposed. This example falls far short of a general formalization of the proposed approach but it does serve to demonstrate that resource allocation rules consistent with this approach can be very different from those implied by a sustainability criterion. A secondary purpose of the example is to highlight a potentially important reason why inefficiency can arise in intergenerational resource allocation, and that democratically consistent policy can play in a role in correcting it.

4. AN ILLUSTRATIVE EXAMPLE

Consider an economy with a sequence of identical generations each comprising n agents. Each agent in generation t has utility function $u(c_t, u_{t+1})$ defined over her own consumption c_t and the utility of her immediate heir u_{t+1}. This representation of Intergenerational altruism has been used extensively before in various contexts.[7] It reflects "non-paternalistic altruism" in the sense that utility is derived from the well-being of another person rather from their consumption. I assume a specific frictional form that is amenable to closed-form solution:

(1) $u_t = \log(c_t) + \beta u_{t+1}$

where $\beta \in [0,1)$ reflects the agent's degree of concern for the well-being of her heir. I assume initially that β is the same for all agents. It should be stressed that β does not represent the agent's private rate of time preference. (In an extended model of multiple-period lived agents a separate parameter for the rate of time preference would have to be introduced). Each generation presumes that the preferences of their heirs will be the same as their own.[8]

Consumption relies on a stream of benefits provided by natural capital, and this natural capital becomes depleted if over-exploited. The transition process for natural capital is given by

(2) $R_{t+1} = (R_t - C_t)(1+\delta)$

where R_t is the stock of natural capital in period t, C_t is aggregate consumption in period t, and δ is the rate of regeneration of natural capital. Sustainability requires that $R_{t+1} \geq R_t$, which in turn requires $C_t \leq \delta R_t/(1+\delta)$. This definition is a natural one in this setting and coincides both with a "preservation of the natural capital stock" requirement and a requirement to "preserve the composite capacity to produce well-being".

Efficiency with homogeneous agents

I begin the analysis by deriving the symmetric intragenerationally efficient consumption rule when all agents have the same β parameter. The planning problem is to choose the consumption path that maximizes the utility of a representative agent in the current generation (generation zero):

(3) $$\max_{c_0} \log(c_0) + \beta u_1$$

$$\text{s.t. } u_t = \log(c_t) + \beta u_{t+1} \quad \forall t$$

$$R_{t+1} = (R_t - nc_t)(1+\delta) \quad \forall t$$

$$R_0 \text{ given}$$

Recursive substitution for u_1 allows this to be reformulated as a standard infinite horizon dynamic programming problem:

(4) $$\max_{\{c_t\}} \Sigma_{t=0}^{\infty}\beta^t \log(c_t)$$

$$\text{s.t. } R_{t+1} = (R_t - nc_t)(1+\delta) \quad \forall t$$

$$R_0 \text{ given}$$

The corresponding Bellman equation is

(5) $$W(R_t) = \max_{c_t, R_{t+1}} \left\{\log(c_t) + \beta W(R_{t+1})\right\}$$

where W(R) is the (current value) value function. It is straightforward to solve this for the following aggregate consumption rule:

(6) $$C_t^* = R_t(1-\beta)$$

In comparison, the maximum sustainable level of aggregate consumption is

(7) $$\bar{C}_t = \delta R_t/(1+\delta)$$

It is clear from (6) and (7) that sustainability is consistent with efficiency if and only if $\beta \geq 1/(1+\delta)$. This means that the efficient path will be sustainable only if agents are sufficiently altruistic and the rate of natural capital regeneration is sufficiently high. If β and/or δ are too small then the stock of natural capital will be continually depleted and the consumption of future generations will tend towards zero. Policy intervention to ensure sustainability in this case would be inconsistent with a democratic setting. If $\beta < 1/(1+\delta)$ then the agents in this economy would unanimously reject a (symmetric) sustainable consumption path over a (symmetric) unsustainable one if given the opportunity to vote. A policy that imposes sustainability in this economy could be implemented only if democracy is suspended.

Efficiency with heterogeneous agents

I now turn to a case with heterogeneous agents. Suppose there are two types of agents: strongly altruistic (type 1) agents with an altruism parameter β_1, and weakly altruistic (type 2) agents with an altruism parameter $\beta_2<\beta_1$. Let α denote the proportion of strongly altruistic agents. Agents of type j presume that their heirs will also be of type j. The intragenerational efficiency frontier for this economy can be derived from a planning problem in which the utility of a representative type 1 current generation agent is maximized subject to some lower bound on the utility of a representative type 2 current generation agent:

$$
\begin{aligned}
(8)\qquad & \max_{c_0^1} \ \log(c_0^1) + \beta_1 u_1^1 \\
& \text{s.t. } u_t^j = \log(c_t^j) + \beta_1 u_{t+1}^j \quad \forall t \\
& \qquad R_{t+1} = (R_t - \alpha n c_t^1 - (1-\alpha) n c_t^2)(1+\delta) \quad \forall t \\
& \qquad u_0^2 = \bar{u} \\
& \qquad R_0 \text{ given}
\end{aligned}
$$

Recursive substitution for u_{t+1} allows this program to be reformulated as

$$
\begin{aligned}
(9)\qquad & \max_{\{c_t^1\}} \ \Sigma_{t=0}^{\infty} \beta_1^t \log(c_t^1) \\
& \text{s.t. } R_{t+1} = (R_t - \alpha n c_t^1 - (1-\alpha) n c_t^2)(1+\delta) \quad \forall t \\
& \qquad \Sigma_{t=0}^{\infty} \beta_2^t \log(c_t^2) = \bar{u} \\
& \qquad R_0 \text{ given}
\end{aligned}
$$

The key to finding a solution to this program is to recognize that at the optimum the second constraint must be satisfied with minimal use of natural capital. The linearity of the transition equation in this example makes it straightforward to exploit this characteristic of the solution. The stock of natural capital at any point in time can be conceptually split into two separate stocks R_t^1 and R_t^2 such that $R_t=R_t^1+R_t^2$, where R_t^1 provides a consumption stream for type 1 agents and R_t^2 provides a consumption stream for type 2 agents. It is then possible to find the minimal value of R_0^2 needed to satisfy the second constraint as the solution to

$$\begin{aligned}(10)\qquad & \bar{R}_0^2 = \min_{R_0^2} \\ & \text{s.t. } \Sigma_{t=0}^{\infty}\beta_2^t\log(c_t^2) = \bar{u} \\ & \qquad R_{t+1}^2 = (R_t^2 - n(1-\alpha)c_t^2)(1+\delta) \quad \forall t\end{aligned}$$

This is just the dual of the standard dynamic programming problem described in (4). It solves for a consumption path given by

$$(11)\qquad c_t^2 = (1-\beta_2)R_t^2/n(1-\alpha)$$

Solution of the system then yields the following minimum value for R_0^2:

$$(12)\qquad \bar{R}_0^2 = \exp\Big[(1-\beta_2)(\bar{u} - \theta)/\beta_2\Big]$$

where $\theta = \Sigma_{t=0}^{\infty}\beta_2^t\log[(1-\beta_2)\beta_2^t(1+\delta)^t/n(1-\alpha)]$. The overall planning program can now be reformulated as

$$\begin{aligned}(13)\qquad & \max_{\{c_t^1\}} \Sigma_{t=0}^{\infty}\beta_1^t\log(c_t^1) \\ & \text{s.t. } R_{t+1}^1 = (R_t^1 - \alpha n c_t^1)(1+\delta) \quad \forall t \\ & \qquad R_0^1 = R_0 - \exp\Big[(1-\beta_2)(\bar{u} - \theta)/\beta_2\Big] \\ & \qquad R_0 \text{ given}\end{aligned}$$

This is now a standard problem with solution

$$(14)\qquad c_t^1 = (1-\beta_1)R_t^1/n\alpha$$

Aggregate consumption for the current generation as a whole is given by

$$(15)\qquad C_0 = (1-\beta_1)[R_0-\bar{R}_0^2] + (1-\beta_2)\bar{R}_0^2$$

Whether or not this level of consumption is sustainable depends on δ, β_1 and β_2, and on $\bar{R}_0^2$. That is, the distribution of utility between strongly and weakly altruistic agents within the current generation, as reflected in $\bar{R}_0^2$, will generally be important in determining whether or not consumption is sustainable. In particular, sustainability is less likely if the utility distribution favors the weakly altruistic over the strongly altruistic. As noted earlier, the utility distribution that arises in this economy will depend on the particular voting rule in place. A natural distributional arrangement to consider is one that provides each group with control over a share of the natural capital stock proportional to its representation in the population. This implies current generation aggregate consumption equal to

$$C_0 = (1-\beta_1)\alpha R_0 + (1-\beta_2)(1-\alpha)R_0 \tag{16}$$

This consumption level is sustainable if and only if $[\alpha\beta_1+(1-\alpha)\beta_2]\geq 1/(1+\delta)$. That is, if enough agents care enough about their heirs then the efficient path based on proportional representation is sustainable. Otherwise it is not. An alternative distributional rule is to vest control of the entire natural capital stock in the hands of the group that constitutes a majority. The preferences of this group would then dictate the consumption levels for all agents in the economy. In this case the efficient path would be sustainable if $\beta_1\geq 1/(1+\delta)$ when $\alpha>1/2$, and if $\beta_2\geq 1/(1+\delta)$ when $\alpha<1/2$. Regardless of the particular distributional rule, it is clear that if the weakly altruistic group constitutes a large enough majority and if their altruism is sufficiently weak then the consumption path will not be sustainable.

Equilibrium with open access

The discussion so far has focused on efficient consumption paths. I have argued that efficiency is not necessarily compatible with sustainability and that policy intervention to ensure sustainability is generally not consistent with a democratic setting. This does not mean that there is no role for policy in directing intergenerational resource allocation. Much of the natural capital stock is characterized by open access. In some cases it is feasible to assign private property rights over natural capital (such as with some fish stocks and trees) but this is not always possible. In this section I derive the Nash equilibrium consumption path when there is open access to natural capital. I focus on the homogeneous agent case since it illustrates the consequences of open access most simply.

Each agent k in generation t perceives the following transition equation:

(17) $$R_{t+1} = (R_t - c_t^k - C_t^{-k})(1+\delta)$$

where C_t^{-k} is consumption by agents other than agent k in period t; it is taken as given by agent k since there is open access to the natural capital stock. I confine consideration to rational expectations equilibria. This means that each agent in the current generation correctly anticipates the equilibrium implications of her consumption decision for the utility of her heir and correctly anticipates that all of her descendants will do the same. The choice problem for agent k in period t can therefore be formulated as

(18) $$\begin{aligned} &\max_{c_t^k} \; \log(c_t) + \beta\hat{u}_{t+1} \\ &\text{s.t.} \; R_{t+1} = (R_t - c_t^k - C_t^{-k})(1+\delta) \quad \forall t \\ &\qquad \hat{u}_{t+1} = \Sigma_{i=1}^{\infty}\beta^i \log(\hat{c}_{t+i}) \\ &\qquad \hat{R}_{t+i} = (R_{t+i-1} - n\hat{c}_{t+i-1})(1+\delta) \quad \forall i \geq 2 \end{aligned}$$

where c_{t+i} is equilibrium per capita consumption in period t+i. This is not a standard dynamic programming problem. However, a solution can be found by positing a time-invariant equilibrium consumption rule of the form $\hat{c}_{t+i} = \alpha R_{t+i}$, and verifying that this in fact solves the program.[9] Solving the problem in this way and imposing symmetry yields the following equilibrium aggregate consumption path:

(19) $$\hat{C}_t = R_t n(1-\beta)/[\beta + (1-\beta)n]$$

Comparing this equilibrium path with the efficient path reveals that equilibrium consumption is too high in early generations. This inefficiency is due to the–open access to natural capital. Each individual in period t recognizes that the natural capital she leaves intact for her descendants will also be available for consumption by the descendants of her fellow citizens. She cannot protect the legacy she leaves. Recognition of this fact leads her to leave less than she otherwise would.[10] It should be noted that this result is sensitive to the form of the utility function. The inefficiency could in principle go the other way: the open access could induce an agent to consume less than is efficient in an attempt to compensate for the fact that the legacy she leaves for her heir may be depleted by others. The inefficiency of the Nash equilibrium implies a role for policy intervention. In this example policy intervention is needed to reduce the rate of consumption but it is conceivable that intervention in the opposite direction may be needed. In either case the appropriate role for policy in a democratic setting is to ensure efficiency rather than to impose sustainability.[11]

5. CONCLUSION

In this paper I have argued that sustainability is an inappropriate guiding principle for the design of policy In a democratic setting. If policy is to be generally implementable then its design must be consistent with the social setting in which it is applied. In a democratic setting that permits individuals to act and vote in accordance with views of distributive justice that are not necessarily consistent with sustainability, policy based on a sustainability criterion will not be generally implementable. The alternative conceptual framework I have proposed is based on three key elements: the relaxation of the distinction between ethics and preferences; the recasting of an intergenerational equity problem as an intragenerational allocation problem; and the requirement that intergenerational resource allocations be intragenerationally efficient.

To recognize that different individuals in a democracy can legitimately hold different and incompatible views on distributive justice is not to say that there is no place for continued debate about the meaning of distributive justice. Such debate is surely valuable. Economists can and should play an important role in that debate. But is it essential that economists carefully distinguish between their philosophizing about the meaning of distributive justice and the more mundane business of guiding implementable policy.

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NOTES

[1] Pearce and Turner (1990, Chapter 15) provide a concise review of some of the ethical views that are most commonly cited to motivate sustainability.

[2] See Chichilnisky (1993) for some recent work in this direction.

[3] As an aside, it seems to me that a requirement to preserve the same opportunities to choose is impossible to fulfill. The second law of thermodynamics renders it physically impossible to leave the planet exactly as we found it over a sufficiently short time interval. To the extent that the next generation follows the current generation instantaneously (there are a continuum of generations) then they cannot inherit exactly what the current generation inherited.

[4] This of course begs the question of how this unacceptability is decided upon. Important as this question is, It is not one on which I need comment here. My scope is more narrow. I am concerned only with the consistency of a guiding principle with the democratic constitution currently in place. The process by which that constitution is established or revised is not directly relevant to that issue.

[5] See Sen (1977) for a discussion of this distinction.

[6] See Howarth and Norgaard (1992) for an example of such a model.

[7] See Ray (1987) for a discussion of this representation.

[8] While I later allow agents to differ according to the size of their β, they could also conceivably differ in their beliefs about what future generation preferences will look like. It should in principle be possible to extend consideration to this issue within the same basic framework.

[9] See Levhari and Mirman (1980). It should be noted that this approach does not guarantee that the posited equilibrium is unique.

[10] Levhari and Mirman (1980) derive an exactly analogous result in the context of a fish war between two infinitely-lived national governments.

[11] Marglin (1963) identifies a different potential source of inefficiency in intergenerational resource allocation. In a model with paternalistic altruism Marglin shows that if the consumption level of the next generation as a group is a public good for current generation agents then there may be too little saving in the economy due to free-riding. The equilibrium discount rate will consequently be too high. This public good problem could co-exist with an open access problem.

An Efficiency Argument for Sustainable Use

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ABSTRACT

"An efficiency argument for sustainable use."

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Sustainability is often viewed as a moral obligation to future generations. The paper adds an argument for sustainability that is entirely based on efficiency and is free from distributional considerations.

Many natural environments admit two uses: (i) a destructive use, where the environment is converted into a private good, used by (a fraction of) the present generation: and (ii) a nondestructive use. where the environment is maintained in its natural form: the environment is thus a public good, useful to both present and future generations. The nondestructive use can often be defended purely on efficiency grounds: this is made precise in a quasilinear model of a finite number of overlapping generations. Efficiency is there equivalent to the maximization of surplus, i.e., the maximization of the sum of the benefits over generations minus the sum of costs.

Two qualifications. First, large transfers of wealth from future to present generations must be physically possible Second, if individual discount the future, then efficiency requires the maximization, not of the sum of utilities, but of a discounted sum of utilities. Efficiency can dictate conservation in Society I and destruction in Society II for two societies that are identical except that individuals discount the future in Society. This is somewhat surprising in overlapping generation models.

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THE UNITED NATIONS INTEGRATED ENVIRONMENTAL AND ECONOMIC ACCOUNTING SYSTEM: AN ENVIRONMENTAL ECONOMICS PERSPECTIVE

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Introduction

Conventional economic accounting, including accounts for assets, income and product as well as input-output accounts, is practiced by most nations of the world because it supports economic policy in several important ways. The national accounts provide measures of a nation's wealth, summary statistics regarding overall economic performance, and an instantaneous but static picture of the flows of economic activity. The description provided by the national accounts of the relationship between outputs of economic processes-the production of goods and services-and economic inputs supporting these processes is critical for economic analysis and policy. An understanding of these mechanisms is essential if the government wishes to influence economic activity predictably. Since their introduction over 50 years ago, the national economic accounts have evolved to respond to changes in the structure of the economy and the analytic and data needs of policy makers.

While there is widespread agreement that the standard national economic accounts provide invaluable information on economic activity, there is also recognition that the standard measures fail to capture other factors which influence social welfare, such as the quality and quantity of environmental resources and amenities. Changes in the environment and in natural resources have not been explicitly included in the economic accounts, principally because ways to measure these changes monetarily were not apparent and thus integrating them with other entries in the accounts was impossible. This neglect of environmental and natural resource activity impairs the functions of the national accounts. First, it fails to include a potentially important category of a nation's wealth and thus future production and consumption possibilities. Second, it provides an overly optimistic picture of economic perfomance in that it omits the effect of negative environmental externalities, such as pollution, on current well-being and the effect of natural resource degradation on future well-being. Finally, the ability to picture relationships between outputs and inputs is degraded since the environment and natural resources generate important input and output services that compete with and substitute for the monetized services that are covered in the conventional accounts.

Integrated environmental and economic accounting systems attempt to address these shortcomings of the national accounts. Three major objectives of the such integrated systems are to: 1) provide an accounting of the interaction of the economy and the natural environment, 2) address sustainable development concerns through proper accounting of both man-made and natural assets, and 3) develop environmentally adjusted measures of product (i.e., a "green" GDP) and income, which may inform on and serve as guidance toward sustainable development policies. The particular system proposed by the United Nations (System for Integrated Environmental and Economic Accounting or SEEA) is designed to expand upon and complement existing economic accounting systems (Systems of National Accounts or SNA) with regard to costing the use (depletion) of natural resources in production and to satisfy final demands, and recording net changes in environmental quality associated with production consumption, and natural events on the one hand and environmental protection and restoration on the other. Using the SNA as the basic framework for an integrated environmental and economic system is not meant to lead to an exclusively economic view of environmental concerns. Rather, it is intended to introduce environmental issues into mainstream economic analysis and policy making through the use of a common framework. Ultimately, the integrated system is intended to provide a suitable database for analyzing sustainable development policies and options.

It should be noted that extending the framework to incorporate environmental concerns is a separate issue from the failure of SNA-type aggregates (e.g., GDP) as welfare measures. Gross Domestic Product is a measure of the market value of economic production; modifyng it to reflect environmental issues will not make GDP a welfare measure. Further, the SEEA also excludes phenomena which take place entirely outside the economic system. For example, the generation of solid waste and gaseous emissions by natural sources and associated assimilation and transformation by ecosystem processes would not be included in the SEEA. Rather, the architects of the proposed system believe that such phenomena are better dealt with by complementary biophysical resource accounts, environmental statistics, and environmental monitoring systems with appropriate linkages to the SEEA. As a result, the SEEA is primarily concerned with the interactions between the environment and economic production, value added expenditures, and tangible wealth.

Over the past decade, a series of international workshops and meetings and a growing body of research and implementation efforts, culminated in the publication of a set of guidelines for integrated environmental and economic accounting (United Nations, 1993). With a few notable exceptions, environmental economists have not played a large role in the development of the accounting framework. Our purpose in this paper is to stimulate a discussion on integrated environmental and economic accounting within the environmental economics community and to challenge members to contribute to the implementation effort drawing on the analytical skills and insights gained from years of studying environmental issues. The first section discusses conceptual issues associated with implementing an integrated environmental and economic accounting system, paying particular attention to how standard welfare analysis concepts can be translated into the measures needed for an accounting effort. The basic structure of the SNA and the proposed extensions to reflect environmental concerns are summarized in the following sections. Results from a preliminary implementation of the SEEA for the U.S. are presented in the fourth section. Given the major omissions and measurement difficulties, these results should not be taken very seriously. Rather, they are intended to illustrate the types of protocols that are necessary for implementing the system, as well as possible adjustments to summary aggregate measures. Finally, summary conclusions and possible extensions are described in the last section.

Conceptual Issues in Implementing Integrated Environmental and Economic Accounting Systems

Conceptually, the natural environment can be viewed as an asset or reproducible capital good which provides a flow of goods and services to the economy over time. When economic use of the "output" of the natural environment results in a permanent or temporary reduction in the quantity of the asset this quantitative reduction is termed depletion. When use results in a reduction in the quality of the natural asset this use is termed degradation. Further, economic use of natural assets also results in feedback effects: depletion of natural resource stocks reduces future flows of goods and services from the environment, degradation due to the disposal of residuals results in costs imposed on third parties. In addition, firms and households may be required to make expenditures for pollution abatement and control. Obtaining a comprehensive picture of advantages and disadvantages of the economic use of the environment in production activities requires estimates of all of these items.

Constructing accounting entries which maintain comparability with the SNA requires the market prices or proxies of market prices, i.e., marginal values exclusive of consumer surplus, and associated quantities. Market values can be used for those natural assets which are connected with actual or potential market transactions, such as subsoil minerals and managed forests. However, environmental functions of these natural assets (e.g., habitat provision and CO_2 sequestration) are in most cases not reflected in the market value of the asset. Directly observable market values for environmental assets (e.g., air, undisturbed ecosystems) do not exist because there are no market mechanisms to convert the value of their generated services into observable market prices. One approach (Peskin, 1989) suggests treating environmental assets as if their services were in fact marketed. However, since it is necessary to record transactions from both "buyers'" and "sellers'" points of view, it raises questions regarding the service quantity to be valued (i.e., the current level of discharges into the environment or the current level of environmental services provided given existing environmental quality) and the appropriate valuation concept to be applied to this service quantity. The second issue arises, of course, because there are no market forces driving buyers' and sellers' marginal valuation to an equilibrium.

The standard macroeconomic analysis of externalities can be used to illustrate these issues. To simplify the discussion, we assume: 1) there are only two users of an environmental asset, 2) their uses of the asset are mutually conflicting and 3) there is an insufficient quantity of the asset to satisify both user's demands. For example, industry may seek to use the air or water to dispose of wastes, and households may seek to use the air or water to support certain levels of health or recreation. The more air or water is used to dispose of wastes the less it is able to support specified levels of health or recreation. Scarcity of the resource ensures nonzero marginal values. The traditional focus of welfare analysis on maximizing total net social benefits leads to a determination of optimal environmental asset use where marginal benefit equals marginal cost. The point we wish to make here is that, at any particular level of air or water quality, there are reciprocal benefits and costs for each user.

From industry's viewpoint there are costs which have already been incurred due to government regulations which restrict their access to the asset (i.e., environmental protection costs) and benefits associated with using the air or water to the current allowable level. This benefit could be viewed as a potential cost to industry, i.e., the potential costs of future air or water regulations if they further restrict industry's access beyond current levels. The first type of cost is recorded in the economic accounts, although their separate identification and reporting as distinct accounting entries is relatively recent,[1] while the second type of prospective cost is not included in the accounts. As noted in Peskin (1989), a complete accounting of all sources of income would include such costs since they measure the value of a nonmarketed factor input. In essence, industry is receiving a "subsidy" from the environment in the form of unpaid environmental waste disposal services.

For households, there are health and welfare "costs" (damages) or environmental repercussion coats associated with the current level of air and water quality, i.e., from being denied access to clean air and water. However, to the extent there has been some improvement in environmental quality due to abatement efforts, some of these damaging effects have already been avoided and benefits realized. Conventional accounts implicitly include damages which manifest themselves in markets (e.g., medical care expenditures) although they are not separately identified.

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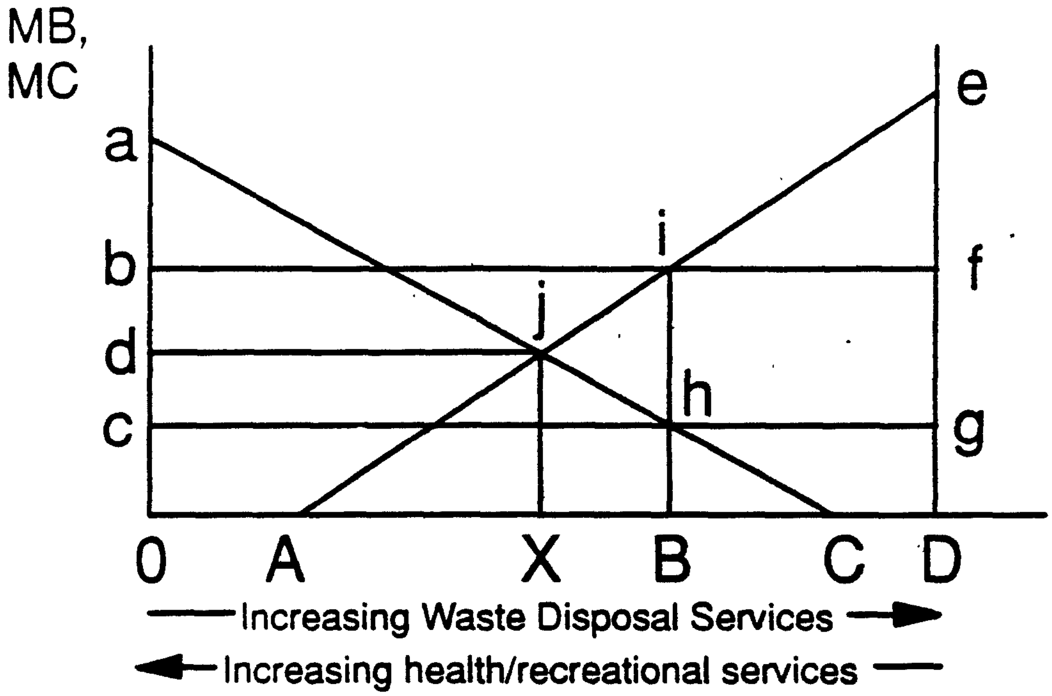
[1] Data on environmental protection expenditures has been collected since 1973. The Bureau of Economic Analysis has published a series of articles entitled "Pollution Abatement and Control Expenditures" in the *Survey of Current Business*, various issues.

Nonmarket service values of air and water, both potential and realized benefits (damages), are not accounted for in conventional accounts. Graphically, we can depict the situation as in Figure 1.

Figure 1.



Them is a total of 0D of the environmental asset. From the industry viewpoint curve aC represents the marginal benefits of being allowed access to the asset or the potential marginal costs if they are not allowed access to the asset. As drawn, industry would not use the entire asset (0D). From the household point of view, Ae represents the marginal benefits of being allowed access to the asset or the potential marginal "costs" (i.e., damages) if they are not allowed access to the asset As drawn industry could use 0A of the asset without causing any damage to households (i.e., them is a non-damaging threshold). We assume that government regulations allow 0B of the asset to be used by industry.

Associated with the current levels of asset use are two "prices": the marginal benefit/cost (b) for households and the marginal benefit/cost (c) for industry. Absent an equilibrating force such as a market, we would not expect in general for b = c. Using marginal values, we can define the following three areas:

- BDfi: The market valued benefits received by households from current policies (i.e., from denying access to industry)
- 0Bhc: The market valued benefits received by industry (or prospective future costs) from being allowed access to the asset.
- OBib: The market valued costs (damages) imposed on households.

The area BCh represents the actual pollution control costs incurred by industry, which are already recorded in GDP. These costs are to be separately elaborated in the SEEA, in aggregate and at the sector level. In extended versions of the SEEA, these costs are separated into external and internal environmental protection activities and a symmetric input-output table developed.

The SEEA captures the notion of competing uses of environmental assets by distinguishing the concepts of "costs caused", i.e., costs associated with economic units actually causing or potentially causing environmental deterioration by their own activities, and "costs borne", i.e., costs which are borne by economic units independent of whether they have actually caused or potentially caused environmental deterioration. In benefit-cost terms, costs caused would correspond to costs, costs borne would correspond to benefits. For example, consider a benefit-cost analysis of a proposed policy to reduce lead emissions to a specified non-damaging level. The analyst might estimate pollution abatement control costs which would fall on the industries emitting the lead and the benefits of expected improvements in human health and welfare which households would enjoy. For environmental accounting purposes, industry is *causing* environmental deterioration or a reduction in the service flow from the natural asset air. Households are *bearing* the repercussions associated with the degradation and presumably would be willing to pay (in terms of reduced consumption) to avoid this burden.

These two valuation concepts correspond to two possible approaches to environmental accounting: 1) accounts which describe the environmental impacts of economic activities, and 2) accounts which describe the condition of the natural environment and its effect on human health and welfare. The latter is a much more complex undertaking since it requires substantially more information (ecological processes, impacts on health, behavioral responses, etc.) which must take into account time and space dimensions. An additional complication is that costs borne will normally require some type of contingent valuation (CV) to estimate the value of adverse health and welfare effects associated with environmental degradation.

The preferred concepts in SEEA are oriented towards "costs caused", i.e., SEEA focuses on which economic agents/activities are responsible (accountable) for deteriorating the natural environment. This focus is driven by both data availability and the relevance of accountability in integrated policies and stainable development management Recent attempts to implement the SEEA have focused on quantitative and qualitative asset use associated with economic production (0B), which is valued at cost (c). Thus, in the SEEA hypothetical (imputed) costs (0Bhc) play a prominent role. The cost of using the natural environment is extended to include costs that *would* have been incurred had the environment been used in such a way that its future use was unimpaired (i.e., the costs that would have been required to maintain natural capital intact). This approach parallels the treatment of man-made capital in the conventional accounts: consumption of fixed capital represents the monetary amount necessary to maintain the current level of man-made assets intact and thus allowing for sustainable fixture income flows. In addition capital consumption estimates the current costs of using fixed assets in production and could be interpreted as constituting a payment to the services of man-made capital.

Relatively little emphasis has been placed on the costs borne concept in the SEEA (area OBib in the diagram). As noted above, determining the impacts of a depleted and degraded natural environment will be a difficult undertaking. However, the SEEA recognizes that it is important to take into account the values accorded to the environment by those (industry and households) who bear the consequences of environmental degradation and depletion. For production activities, costs borne are to be estimated using actual or imputed market values. That is, the reduction in the market value of a natural asset due to quantitative depletion or qualitative degradation (which may be partly counterbalanced by restoration activities of the government) would be treated as a cost and integrated into the production accounts of the SEEA. For households, the SEEA acknowledges that a significant part of the valuation of repercussions associated with a deteriorated natural environment will require willingness to pay or CV methods.

Many accountants doubt whether it is possible to determine monetary values for preferences in the absence of markets (see Hueting, 1980, chap. 4.5), and remain skeptical about the feasibility of applying CV methods in a national accounting framework. The SEEA also expresses reservations about CV, stating "Use of the contingent valuation approach in environmental accounting is still in an exploratory stage. Further research and discussion are needed. The following proposals therefore provide only a generic framework for further experimentation with this valuation method and related accounting procedures" (UNSO, 1993). This reluctance on the part of accountants to use CV is not surprising given the focus of conventional economic accounting on production, transactions, and costs. Accountants would be the first to acknowledge that the accounts record market transactions, not values, and hence accounting aggregates are not measures of welfare.

In summary, both the costs caused and costs borne concepts involve actual costs, which are recorded in the SNA although not separately identified and imputed environmental costs, which are recorded as additional cost items in the SEEA. Nonmarket valuation approaches will be required to estimate imputed environmental costs although the costs borne concept would require additional, relatively more controversial, alternative valuation concepts such as CV. The SEEA recommends using maintenance costs to estimate costs caused since the data are more reliable and available and responsible economic agents are identified and held accountable. It is also similar to approaches followed for other non-marketed goods and services. For certain non-marketed goods and services (e.g., subsistence farming agricultural products, own-account production of housing services) conventional accounts base valuation on prices of similar products which are marketed (e.g., market prices of agricultural products, market housing rentals). However, where such market information is lacking, non-market goods and services are valued at cost (e.g., government services).

United Nations System of National Accounts (SNA)

The revised SNA constitutes Version I of the SEEA. The parts of the SNA that form the conceptual basis for the development of the SEEA are the supply and use table of produced goods and services and the non-financial asset accounts, which includes both produced (man-made and natural) and non-produced natural assets. These two segments of the SNA are described below.

Supply and Use accounts

The SNA supply and use accounts record production activities which took place during the accounting period. The total production by the economy, augmented by production from the rest of the world (i.e., imports) is then available to be used to satisfy intermediate and final demands. The supply and use accounts attempt to measure these transactions, recording them from both transactors' points of view. The supply-use accounting identity is:

(1) $P - M = Ci + C + I + Ex$

where P = production, M = imports, Ci = intermediate consumption, C = final consumption, I = gross capital formation (or Investment) and Ex = exports. A second identity defines gross product or value added (Y) as the difference between total production (P) and intermediate consumption (Ci):

(2) $Y = P - Ci$

When this income identity is substituted into (1), the familiar domestic-product identity emerges:

(3) $Y = C + I + (EX - M)$

Asset Accounts

The SNA asset accounts record all stocks and flows associated with changes in those stocks which are defined as part of the economy. Valuation is normally restricted to market values, although certain nonmarketed goods and services are included which are valued either on the basis of prices of similar products and services that are marketed (e.g., owner occupied housing) or at cost (e.g., government services). Relationships between the environment and the economy are viewed from an economic perspective only, i.e., the environment is viewed in terms of its use in economic production. However, a key criticism of conventional accounting is that the use of environment is not treated as a cost and so is not reflected in summary measures such as Net Domestic Product (NDP).

The SNA asset accounts categories include opening and closing stocks, capital formation, other changes in assets, and revaluation (holding gains/losses). These accounts explain changes between opening and closing stocks associated with flows during the accounting period. For both produced and nonproduced economic assets, the balances are defined as follows:

(4) $K_1 = K_0 + I - Depr. + OC + Rev$

where K_1 = closing stocks, K_0 = opening stocks, I = gross capital formation Depr. = consumption of fixed capital (or depreciation), OC = other changes in assets, and Rev = revaluation (i.e., holding gains or losses).

Certain elements of the capital formation account (i.e., gross fixed capital formation and consumption of fixed capital) intersect with the supply and use accounts described above. Gross capital formation refers generally to produced assets, although it also includes some additions to non-produced assets (e.g, reforestation). Gross capital formation is included in calculations of GDP as shown in equation (3). Subtracting consumption of fixed capital from both sides of equation (3) yields the net domestic product identity:

(5) $Yn = C + In + (Ex - M)$

where Yn = net product and In = I - depr. or net capital formation. Net domestic product may be considered a measure of Hicksian income (i.e., the maximum amount of income a nation can consume which will leave the nation as well off at the end of the period as it was at the beginning of the period). Hicksian income is thus “sustainable” and many argue that measures such as NDP represent a first step in developing sustainable development indicators. Consequently, many in the environmental policy community have focused on “greening” the NDP.

During the recent revisions to the SNA (United Nations, 1992) it was recognized that a more detailed description of assets was required. This was accomplished in part through the expansion of the asset boundary. In the revised SNA, the definition of assets was expanded to include all assets over which ownership rights can be enforced and which provide economic benefits to their owners. Conceptually, the asset boundary includes natural assets, both those which are owned and managed or cultivated directly by humans and those which are owned but not managed or cultivated. Within the revised SNA asset boundary, two types of nonfinancial assets can be distinguished: 1) produced assets and 2) non-produced assets. Produced assets may be man-made assets (e.g., buildings, equipment, inventories of harvested crops) or developed natural assets (e.g., cultivated biological assets such as livestock for breeding, fish stocks, orchards, and timber tracts). Non-produced natural assets include land, subsoil assets, uncultivated biological assets such as wild fish and forests, and water resources.

The other changes in assets account is particularly important for environmental analysis since it contains information on the impact of the environment on natural and other assets. This account contains economic appearance of non-produced assets (e.g., additions to proven oil reserves, additions to timber reserves through the logging of virgin forests), natural growth of uncultivated biological resources, and economic disappearance of non-produced assets (e.g., depletion of subsoil assets and forests, degradation of non-produced assets). However, these entries are not recorded as part of the production accounts and therefore do not affect the calculation of GDP or NDP. For example, if a site is degraded because it is used to dispose of solid waste, the market price of the natural asset (land) may reflect this degradation which would be recorded as other changes in assets. Essentially this reduction in the market price of the land is not considered a cost of production.

The use of the terms “economic appearance” and “economic disappearance”, especially with respect to non-produced assets, reveals one difficulty facing conventional national accountants. Natural resources “appear”, not as a result of economic activity but rather as a result of ecological processes. Consequently, they are considered “free gifts of nature”. Of course since they are “free" they are presumably available in unlimited quantities. Expenditures to develop these gifts (e.g., unproved mineral reserves can be developed into proved mineral reserves) are recorded as gross capital formation and the natural resource is considered a non-produced economic asset. What is not clear is how to record the additions to (appearance of) the natural resource stock itself. Similarly, these resources “disappear” as they are used up. Unlike appearance, however, disappearance is clearly tied to economic activity, which suggests that an entry to reflect this depletion should appear in the production accounts in a way that parallels depreciation of man-made capital. Initially, the U.S. national accounts did include such entries beginning in 1942. Dissatisfaction with this asymmetric treatment of natural resources (i.e., entries for depletion but no entries for additions), led to the removal of depletion from the national accounts in 1947.

A simplified SNA supply and use account with asset balances is depicted below based on these accounting identities and protocols.

SNA Supply and Use Accounts with Asset Balances for Economic Assets
(SEEA Version I)

				Economic Asset Balances	
Element	*Production*	*Rest of World*	*Final Consumption*	*Produced Assets*	*Nonproduced Assets*
Open Stocks				**K_0.p**	**K_0.np**
Economic Supply	P	M			
Economic uses	*Ci*	Ex	c	I.p	I.np
Gross Product	Y				
Capital consumption (Depreciation)	Depr.			Depr.	
Net Product/ Net Capital Formation	Yn			In	
Other Changes in Assets				OC.p	OC.np
Holding gains/losses				Rev.p	Rev.np
Closing Stocks				**K_1.p**	**K_1.np**

United Nations System for Integrated Environmental and Economic Accounting (SEEA)

In general, the SEEA advocates following principles and rules established for national economic accounting systems. For example, the SEEA observes the SNA'S production boundary, uses SNA methods of analyzing costs and outputs and incorporates the same accounting identities between supply and use of products and between value added and final demand. This allows the integration of environmental information into established economic accounting systems. The possibility of extending the framework to include environmental welfare effects (e.g., damages associated with the impairment of human, health, recreation, and other aesthetic values) is also acknowledged.

Distinguishing the boundary between economic and ecological systems is difficult and subject to a substantial amount of controversy. From an ecological point of view, the economy is part of nature; integrated accounting systems should thus determine ecologically sound balances between nature and human activities. From an anthropocentric (economic) point of view, the natural environment is considered only in terms of how it affects human beings, especially in the context of economic activities; integrated accounting systems should thus retard those natural functions which are exploited by human beings. The SEEA attempts to reflect a synthesis of the ecological and economic points of view. That is, the economy is not viewed solely as part of the environment and the environment is not viewed solely in terms of its economic usefulness. Several, often complementary, approaches to natural resource and environmental accounting are presented in the SEEA with the aim of developing compatible data sets which can be used to analyze environmental-economic relationships.

Finally, most accountants believe that it is important to make a distinction between accounting and analysis. In their view, the accounts should rely to the maximum extent possible on observed data and not on imputations or modeling. In many cases, modeled output is used to characterize the environment. This raises the question whether environmental modeling should be included in the accounts (i.e., considered as a generator of quantity and quality data for the accounts) or should such modeling be considered analysis which uses the data contained within the accounts. For example, the U.S. National Income and Product Accounts contain imputations (modeling) for the value of owner-occupied housing and the national accounts data is used in macroeconomic models of the U.S. economy (e.g., DRI, Wharton, Jorgenson-Wilcoxen, etc.).

Implementation of the SEEA

The SEEA is designed to be as comprehensive as the data will allow, while maintaining consistency within the system and close linkage with conventional national economic accounts. Given the lack of consensus on environmental accounting methods and data constraints, implementation of the SEEA requires a flexible, “building blocks” approach. Beginning with the revised SNA (Version I of the SEEA), four stages of implementation are described in the SEEA Handbook (UNSO, 1993). These are:

1. Reformatting and disaggregation of the SNA (Version II),
2. Physical accounting (Version III),
3. Imputed environmental costs, using alternative valuation methods (Versions IV. 1-3), and
4. Possible extensions (Versions V.1-6), including extending the production boundary to include household activities and environmental services produced by nature, and input-output analysis.

The fourth stage involves approaches which remain controversial and for which there is no general consensus on their feasibility and desirability. The SEEA handbook recognizes that they may become important for particular analyses and briefly covers these possible extensions to the SEEA. We do not discuss them further in this paper.

In Version II, environment-related monetary flows within the production and asset accounts are identified and further elaborated. The relevant portions of the supply and use tables of produced goods and services are disaggregation with respect. to the actual expenditures for: 1) prevention and restoration of negative environmental impacts associated with economic activities, as defined in the draft classification of environmental protection activities, and 2) for mitigating the repercussions associated with a degraded natural environment which encompasses avoidance activities (e.g., installation of water purifiers) and treatment of damages caused by environmental deterioration (e.g., purchase of additional health and cleaning services). Together the actual expenditures associated with environment-related activities are called actual environmental costs and comprise environmental protection costs and repercussion costs. All actual environmental costs are borne by the economic units financing the expenditures, although they may not have caused the environmental deterioration.

The SNA classification of non-financial assets is modified to more explicitly reflect natural assets. In particular, land is broken down to separately identify soil and air is introduced as an asset. although no monetary value is applied to it (i.e., it is to be used in physical accounting and in estimating imputed environmental cost. As noted above, within the SNA non-financial asset accounts. the other changes in assets is particularly important.

The data in other changes in assets are grouped into categories of depletion, degradation (as reflected in market values), other accumulation (additions to mineral reserves, natural growth of non-cultivated biota, etc.), and other volume changes (i.e., changes which are due to political, natural or other non-economic causes which affect the economic system). Thus Version II of the SEEA (shown below) will look much like the SNA presentation with additional entries detailing the environment-related information.

SEEA Version II. Supply and Use Accounts with Asset Balances for Economic Assets, Elaboration of Environmental Protection Costs, Environmental Repercussion Costs, and Elements of Changes in Other Assets

				Economic Asset Balances	
Element	*Production*	*ROW*	*Final Consumption*	*Produced Assets*	*Nonproduced Assets*
Open Stocks				**K_0.p**	**K_0.np**
Economic Supply Excluding EP, ER	P.ex.EP	M			
EP Activities	**P.EP**				
ER Activities	**P.ER**				
Economic uses Excluding EP,ER	*Ci.ex.EP-ER*	Ex	C.ex.EP-ER	I.p.ex.EP-ER	I.np
EP Expenditures	**Ci.EP**		**C.EP**	**I.p.EP**	
ER Expenditures	**Ci.ER**		**C.ER**	**I.p.ER**	
Capital consumption (Depreciation) Excluding EP,ER	Depr.ex.EP-ER			Depr.ex.EP-ER	
EP assets	**Depr.EP**			**Depr.EP**	
ER assets	**Depr.ER**			**Depr.ER**	
Net Product/Net Capital Formation	*Ynl*			*Inl*	
Other Accumulation					**OA.np**
Depletion					**Depl.np**
Degradation					**Degr.np**
Holding gains/losses				Rev.p	Rev.np
Closing Stocks				**K_1.p**	**K_1.np**

Version III focuses on a physical accounting of the environment. The SEEA physical accounts are based on the concepts of materials/energy balances and natural resource accounting. Materials/energy balances show the material input from the natural environment into the economy, the use and transformation of these inputs in economic activities, and their return to the environment. Natural resource accounts focus on natural resource stocks, such as biological, subsoil, and water assets, which are valuable from an economic point of view as well as changes in the quantitative and qualitative characteristics of those stocks. As noted previously, the SEEA does not attempt to provide information on the transformation processes which take place entirely within the natural environment. Nor does the SEEA provide a complete assessment of the transformation processes within the economy. Rather, the physical information in the SEEA is limited to recording flows from natural assets to the economy and residual flows back to the environment at an aggregate level.

An additional limitation is the lack of spatial detail in the SEEA natural asset accounts (i.e., the SEEA is intended to be a national system of accounts). Detailed regional-level accounts, based on various graphical information systems, are needed to adequately describe the natural environment. These regional accounts could be linked to the SEEA to provide a national picture, although it remains to be seen whether such aggregate accounts yield useful information for environmental policy purposes. Similarly, it would be desirable to describe the flows of natural resource inputs, products, and residuals in a detailed breakdown by type of input and output. Unfortunately, existing data on production and consumption activities is usually not sufficiently detailed to provide this information.

Flows of residuals (pollution) are recorded at the point in time they are generated by a particular economic activity. Similarly, the impact of these residuals on ambient conditions are shown only as environmental quality changes over the time period covered by the accounts. The impacts of many long-term environmental problems such as global climate change, stratospheric ozone depletion, and accumulation of toxics will thus be recorded when they occur. For example, the SEEA would show emissions of greenhouse gases which occurred in the last year, the impacts of climate change would not be recorded until they occurred, which may not happen for many years. The SEEA is not intended to record or predict future impacts and alone it will not be able to address many of the concerns surrounding sustainable development. Rather, the SEEA is designed to provide data to ecological-economic models which would capture the dynamics of environmental transformations.

Using materials/energy balances and natural resource accounts for the physical accounts of the SEEA does not mean that SNA concepts have to be modified. Linkages between the monetary data in the SNA and the physical data in the SNA can be accomplished by ensuring that corresponding items in the two systems can follow the same definitions and classifications. Alternatively, bridging matrices which applied compatible concepts at the interface between the SNA and the physical data in the SEEA could be used. This procedure would be necessary when there is no direct counterpart in the SNA for the physical data in the SEEA.

Presentation of environmental-economic interactions in only physical terms would severely limit the usefulness of the SEEA. If the SEEA is to truly integrate economic activities and environment effects, the relative importance of each needs to be determined and results aggregated, which in turn requires a common metric. Version IV of the SEEA introduces imputed environmental costs in order to provide a more comprehensive picture of environmental and economic interactions. Three different valuation methods are proposed:

1. Costs borne at market values by industry (Version IV.1),
2. Costs caused at maintenance costs (Version IV.2), and
3. Costs borne at market values by industry and at contingent values by households (Version IV.3)

Each approach involves imputing additional costs to economic activities, either through the rearrangement of existing information in the SNA (Version IV. 1) or by estimating costs using hypothetical control costs or other non-market (e.g, CV) methods. An additional asset category, non-produced environmental assets, is also appended to the Version I SEEA table.

Version IV.1. Imputed environmental costs at market values

This version of SEEA involves shifting the depletion and degradation items in the other changes in asset accounts into the production accounts. That is, the reduction in natural asset market values associated with depletion and degradation are treated as a cost. Corresponding positive cost items are imputed to the economic agents which cause the depletion and degradation and appear in the production column. In general it will be difficult to identify changes in market values of natural assets due to degradation. The accumulation items are shifted into the capital formation account and a parallel negative counterpart appears in non-produced environmental assets (OA.env). This element is intended to reflect the transfer of environmental assets and their services to economic activities. Two Environmentally adjusted net Domestic Product measures (EDP1) can be defined as follows:

$$(6)\qquad \begin{aligned} \mathrm{EDP1} &= \mathrm{C} + (\mathrm{I}n + \mathrm{OA.np} - \mathrm{OA.env} - \mathrm{Depl.np}) + (\mathrm{Ex} - \mathrm{M}) \\ &= \mathrm{C} + (\mathrm{I}n - \mathrm{Depl.np}) + (\mathrm{Ex} - \mathrm{M}) \end{aligned}$$

$$(7)\qquad \begin{aligned} \mathrm{EDP2} &= \mathrm{C} + (\mathrm{I}n + \mathrm{OA.np} - \mathrm{OA.env} - \mathrm{Depl.np} - \mathrm{Depr.np}) + (\mathrm{Ex} - \mathrm{M}) \\ &= \mathrm{C} + (\mathrm{I}n - \mathrm{Depl.np} - \mathrm{Degr.np}) + (\mathrm{Ex} - \mathrm{M}) \end{aligned}$$

Version IV.2 Imputed environmental costs at maintenance costs

Maintenance costs have been discussed in the context of costs caused above. The use of maintenance costs reflects a conservationist view toward the environment. Given the uncertainty with respect to long-term environmental problems and the potential for irreversible damage a high degree of risk aversion may be prudent. In this situation many have argued for, at a minimum, the maintenance of the current level of environmental quality. Maintenance mats are also closely related to sustainable development concepts, in that they measure the costs that would have been required to keep the natural environment intact during the accounting period. These costs are hypothetical since an actual use did take place which affected the environment. Of course, calculation of depreciation of freed assets is also hypothetical since it is not know whether actual investments will be made which will maintain the capital stock. Using the maintenance coat approach in combination with traditional depreciation measures allows for both the maintaining of income flows and preserving the natural environment intact.

Ideally determination of maintenance costs should be based on: 1) data which describes physical changes in the natural environment caused by economic activities, 2) analysis of ambient conditions to determine whether depletion or degradation is occurring,
3) determination_of non-damaging (sustainable) environmental quality levels (e.g., quantitative standards), 4) activities (e.g., discharge reductions) needed to meet these standards and 5) an estimate of the costs associated with these activities. Several types of actions aimed at preventing or restoring environmental deterioration could be undertaken.
Depletion of natural assets can result in a reduction in economic production. Reducing economic production or altering consumption patterns can reduce the generation of residuals. Changes in the composition of output, substitution of inputs, technological change and environmental protection activities can all prevent deterioration or restore the natural environment. Calculation methods will depend on the specific activity considered. For example, in the case of pollution, imputed environmental costs could be based on reductions in net value added or household consumption expenditures, substitution costs and environmental protection costs. Estimated degradation costs should be based on the most efficient methods for meeting environmental standards. One alternative for imputed depletion costs has been proposed by El Seraphy (1989), which allocates part of the operating surplus for alternative investment.

Imputed environmental costs are associated with the environmental media which directly receive the residuals generated by economic activities. The ultimate destination of these residuals is not taken into account. For example, acidic deposition and consequent damages to terrestrial and aquatic ecosystems due to the emissions of sulfur oxides into the atmosphere by electric utilities are not recorded. Similarly, unless transported by economic agents outside the territorial boundaries of the country, the transfer of residuals to another countries is not considered. In Version IV.2 of the SEEA, there are additional entries, particularly degradation of environmental assets.

Version IV.3 Imputed environmental costs at market and contingent values

The SEEA handbook raises several concerns regarding CV and its use in environmental accounting. The SEEA provides only a generic framework within which further research, discussion, and experimentation with CV and related accounting procedures are to be explored. While the SEEA does not emphasize the use CV, neither does it dismiss the technique outright.

The SEEA suggests that CV questions be posed in terms of specific consumption activities and expenditures that households would be willing to forego. The SEEA also notes that the number and order of environmental concerns raised may influence respondents willingness to reduce consumption. To deal with this problem, the SEEA recommends asking for total willingness to forego consumption as a first step and then ask for the proportion that respondents would allocate to alleviating specific environmental-concerns. Finally, households should be willing to reduce their consumption by at least actual repercussion costs, suggesting that CV studies should focus on respondents additional willingness to pay beyond the defensive expenditures they currently make. An alternative approach would be to present households with substitute consumption patterns and activities which are less environmentally damaging. Differences in expenditures associated with the offered change in activities could be used to represent the value of lost environmental quality.

Imputed repercussion costs, based on contingent values, are recorded as reduction in individual consumption and as additional costs of economic activities of households. An extended concept of household production, as discussed in Version V, would be needed to develop a comprehensive picture of the distribution of imputed repercussion costs. To avoid extending the production boundary of the SNA to include household production, a new row (Shift of environmental costs) is introduced and imputed repercussion costs are shifted from consumption to domestic production of industries. This shift allows the SEEA to fully account for the social cost of environmental degradation.

The table below is based on Version IV.2 and shows the types of changes that could be made to the basic SEEA. Corresponding entries in the additional column, Non-produced Environmental Assets (OA.env, Depl.env, Degr.env) and in the production and economic asset accounts can thus explicitly reflect interactions between environmental assets and economic activities. Corresponding definitions for EDP1 and EDP2 would be:

(8) $\text{EDP1} = C + (I_n - \text{Depl.np} - \text{Depl.env}) + (Ex - M)$

(9) EDP2 “ $C + (I_n - \text{Depl.np} - \text{Depl.env} - \text{Depr.np} - \text{Degr.env}) + (Ex - M)$

Pilot Implementation of SEEA for the U.S.

This section outlines the environmental components of the SEEA. These components can quickly add up to a dizzying array of rows and columns of data to any reader unfamiliar with the certain conventions of economic accounting in general and the specific organization of the SEEA. To make it easier to understand the final table that consolidates all of the major SEEA components achieved in this pilot implementation, the description in this section proceeds component by component, building up the table until all of the pieces are represented. Keeping this in mind may help the reader proceed through this demonstration more effectively. Before the final, consolidated table, four tables are presented. These tables focus on the following in turn: disaggregation of the accounts to show the role of environmental protection in the economy, adjustments to NDP to reflect the depletion of natural resources (EDP1), the linkage of EDP1 to asset balances for natural resources, and adjustments to NDP to integrate environmental degradation into the accounts (EDP2) and the linkage of EDP2 to balances for environmental assets.

Disaggregation of Economic Accounts

Information that is already in the accounts can provide insights into the role that the environment and environmental protection play in economic activity. For example, using input-output analysis and by isolating environmental protection expenditures currently undertaken by economic agents it is possible to illustrate the contributions of an environmental protection sector to each of the conventional macroeconomic aggregates.

In the shaded area of Exhibit A the contribution of such a instructed environmental protection industry to U.S. value-added (GDP) is indicated, from the work of Nestor and Pasurka (1994). Although the level of environmental protection effort by the U.S. has commonly been gauged by comparing environmental protection expenditures directly to GDP, such a comparison is misleading because the two measures are not on equivalent terms. Using the value-added estimate for the environmental protection is more appropriate. In 1987, the environmental protection sector's share of value-added was approximately 0.6% ($28 billion).

SEEA Version IV.2. Supply and Use Accounts with Asset Balances for Economic Assets, Environmental Protection, Contingent Valuation of the Repercussion Costs of Households and Capital Accumulation at Maintenance Values

				Economic Asset Balances		
Element	*Prod*	*ROW*	*Final cons*	*Produced Assets*	*Non-produced Assets*	*Non-produced Environmental Assets*
Open Stocks				$K_0.p$	$K_0.np$	
Economic Supply	P	M				
Economic uses	Ci	Ex	c	I.p	I.np	
Other accumulation					OA.np	OA.env
Capital consumption (Depreciation)	Depr.p			Depr.p		
Depletion	Depl.np Depl.env				Depl.np	Depl.env
Environmentally adjusted net product: EDP1	EDP1					
Degradation	Degr.np Degr.env				Degr.np	Degr.env
Environmentally adjusted net product: EDP2	EDP2					
Other Changes in Volume				OC.p	OC.np	OC.env
Holding gains/losses				Rev.P	Rev.np	
closing stocks				$K_1.p$	$K_1.np$	

Exhibit A.
Environmental Accounts for the United States, 1987
Environmental Protection Expenditures Separately Identified
($ Millions)

	Economic Activities				
				Economic	Assets
	Reduction	Rest of World	Final Consumption	Reduced Assets	Non-Prod. Assets
Opening Assets				$11,571,629	$479,025
Fixed Assets				$10,535,200	
Inventories				$1,030,700	.
Timber				$5,729	
Oil					$166,527
Natural Gas					$138,209
					$155,678
					$18,611
					K0.np.ec.h2o
Economic Supply	$8,042.812	$507,100			
Economic Uses	$3,502.812	$364,000	$3,933,800	$749,300	
Product GDP Env. Protection	$4,540,000 [28,172]	($143,100)	$3,933,800	$749,300	
Depreciation	$502,200			($502,200)	
Net Product: NDP	$4,037,800	($143,100)	$3,933,800	$247,100	

EDP1: Adjusting NDP to Reflect Natural Resource Depletion

EDP1 is a measure of NDP that has been adjusted for the depletion of marketed natural resources. In this pilot implementation for the U. S., the focus is on six natural resources. They are timber, oil, natural gas, coal, selected minerals, and water. These six were judged to be important because of their value or the sheer volume of their use in economic activities.

The shaded area of Exhibit B highlights the new components added to measure the depletion of these six natural resources and the resulting estimate of EDP1 in 1987. These figures show how natural resource adjustments in national economic accounting can present a more pessimistic view of the economy's performance. For the U.S., the revision is small, only 0.8%. Even though even a small difference in measures of output can accumulate to a large amount in absolute terms, this revision still appears to be minor. This finding is not surprising for the U.S. because of the diverse nature of the economy. Nonetheless, it has been argued that this revision results m a dramatic downward revision in the rate of return that can be derived from national economic accounts for the associated industries (Bureau of Economic Analysis 1994). This result may be informative for national economic policymakers but it probably is not new information for private investors in these industries who should already be aware that natural resource production or retraction depletes the assets of the industry. Given the results of this pilot case, it appears that including natural resource depletion in U.S. national economic accounts matters for keeping them as complete and comprehensive as possible even if the results do not appear to be significant. On this point, others

Exhibit B.
Environmental Accounts for the United States, 1987
Resource Depletion
($ Millions)

	Economic Activities		
	Production	Rest of World	Final Consumption
Opening Assets			
Fixed Assets			
Inventories			
Timber			
Oil			
Natural Gas			
Coal			
Minerals			
Water			
Economic Supply	$8,042,812	$507,100	
Economic Uses	$3,502,812	$364,000	$3,933,800
Product: GDP	$4,540,000	($143,100)	$3,933,800
Env. Protection	[28,172]		
Depreciation	$502,200		
Net Product: NDP	$4,037,800	($143,100)	$3,933,800
Environmental Uses			
Timber Harvests	$130		
Timber Net Growth	($159)		
Oil Extraction	$17,793		
Oil Discoveries			
Nat. Gas Extraction	$11,617		
Nat. Gas Discoveries			
Coal Mining	$532		
Coal Discoveries			
Mineral Extraction	$824		
Mineral Discoveries			
Water Extraction	$10,869		
Water Returned	($7,577)		
Net Product: EDP1	$4,004,071	($143,100)	$3,933,800

may disagree. Having the information publicly and widely available, as they would be if the SEEA were fully implemented, is consistent with an important function of the accounts - to provide access to a common set of data so that many users can evaluate them and draw their own conclusions.

Computation of EPD1

The computation of each of the depletion charges presented in Exhibit B is described briefly below. Greater-details are currently available only in an unpublished document (Abt Associates, 1994).[2] In all circumstances, a net price approach was applied to the change in the resource stock in question. This approach requires information on the opening and closing stocks of the resource. to infer physical depletion, and an estimate of the net price or its analogue. Each resource is considered in turn below.

The growing stock of timber for 1987 was interpolated from U.S. Forest Service inventories conducted in 1986 and 1991. Stocks grew from 756 billion cubic feet to 762 cubic feet. To value the stocks and harvests, information from competitively bid sales of U.S. Forest Service timber was used. These values exclude production costs and therefore were taken as estimates of net prices. The opening and closing stocks of timber were valued at $5.729 billion and $5.758 billion respective y. The increase in the stock, approximately $29 million, reflects the fact that net natural growth ($159 million) exceeded removals ($130 million) by this amount. The net differences is subtracted from NDP to calculate EDP1.

Information on crude oil and natural gas reserves and production were obtained from the U.S. Department of Energy's Energy Information Administration (EIA, 1988). The net prices of oil and gas were derived from estimates of "resource values," a net income concept, developed for 1981 by Stauffer and Lennox (1984).[3] A central assumption for this derivation was that resource values as a proportion of revenues were constant between 1981 and 1987. In the calculation of EDP1, only the depletion of oil and gas stocks is **considered.**[4] Based upon the net price method, oil extinction was valued at $17.8 billion and natural gas extraction at $11.6 billion. Together they account for 87% of the depletion that constitutes the difference between conventional NDP and EDP1.

Statistics on coal production and reserves were derived from EIA and U.S. Department of Commerce data (EIA, 1989; U.S. Department of Commerce, 1989). As was the case for oil and gas, only the extraction of coal figures in the calculation of a depletion charge against conventional NDP. In the absence of better information on production costs, an estimate of the resource value of coal in 1987 was calculated from industry accounting data. Net revenue for the coal industry was estimated by adding operating income and coal production taxes and subtracting income taxes from their sum. The resulting depletion charge for coal was $532 million.

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[2] The authors would like to acknowledge the capable assistance of Todd Aagaard in the compilation of the EDP1 data.

[3] Their estimate of resource value is the sum of lease and land acquisition of non-producing acreage, taxes other than income taxes, royalties, and windfall profits taxes.]

[4] As will be shown below, the SEEA treats discoveries in the asset balances, not in the measures of flow. The logic is that no production was involved since these are nonrenewable resources.

Statistics on production and reserves of more than eighty minerals are routinely collected by the Bureau of Mines (1988). Some production occurred for the majority of these minerals in 1987 but it was not possible to characterize the depletion of each one because of data constraints. For example, to preserve confidentiality, the Bureau of Mines did not release data on the domestic production of fourteen minerals. Furthermore, the Bureau estimated certain essential financial information only for selected minerals. For these minerals, Bureau of Mines' estimates of taxes and royalties per unit of minerals, averaged over facility lifetime with a 15% discount rate, were applied to the 1987 prices of the minerals to calculate their depletion charge. The resulting depletion charge for twelve minerals was $824 million.[5]

The U.S. Geological Survey (USGS) publishes estimates of water use every five years. For eight categories of users (domestic, commercial, irrigation, livestock, industrial, mining, and thermoelectric power), the USGS estimates total use and consumptive use. Consumptive use means that the water used dissipated, was incorporated into products or crops, consumed by humans or livestock, or otherwise removed (USGS, 1988). For this pilot study, the physical depletion of water was derived from net water use - the difference between water extinction (from surface or ground sources) and water returned. Data on water prices from the 120 largest metropolitan areas (Arthur Young & Company, 1988) and on government capital and operating and maintenance expenditures from the Department of Commerce (reported in EPA, 1990) were used to calculate net water prices. The average net. price of publicly-supplied water, weighted by categories of use, was $0.09 per 1000 gallons. The estimated depletion of water was $3 billion, reflecting the difference between water extraction ($10.9 billion) and water returned ($7.9 billion).

Linkage of EDP1 to Asset Balances

An important feature of SEEA is its characterization "of the contribution of the environment to economic activities. This contribution is depicted as a transfer from the environment to the economy. Natural resources that have not yet become "economic" (having a net price greater than zero) are defined as being environmental assets. Only once these natural resources are proven, which here is equated with being "discovered" do they become economic. At this point, they are transferred from the environmental asset balance to the economic asset balance. While conventional accounting would show a gain in wealth with the discovery of a natural resource- like oil, the SEEA does not. Because the discovery is treated as a transfer, overall wealth stays constant as long as none of the oil is depleted. For example, in 1987 the discoveries of oil were worth $20 billion. In Exhibit C, this discovery is shown as a deduction of oil from the environment asset balance and an increase in non-produced economic assets.

It has already been demonstrated that SEEA only the depletion' of oil and other non-producer natural resources is considered in adjusting NDP. The balance sheets for non-produced assets also incorporate this depletion. So, for example, the $17.8 billion depletion charge for oil that was included in the calculation of EDP 1 is also included in the asset balance for oil. Overall, in 1987, there was a growth in oil as an economic asset of $2.2 billion given discoveries and depletion of $20 billion and $17.8 billion respectively. Natural gas is shown in analogous terms, with a transfer from the environment of $8.4 billion. Natural gas, in contrast to oil, declined as an

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[5] The twelve minerals were aluminum, asbestos, barite, copper, gold, lead, molybdenum, phosphate rock, potash, silver, sulfur, and zinc.

Exhibit C.

Environmental Accounts for the United States, 1987

Resource Depletion

($ Millions)

	Economic Activities					Environment
				Economic Assets		Non-Prod. Environment. Assets
	Production	Rest of World	Final Consumption	Produced Assets	Non-Prod. Assets	
Opening Assets				$11,571,629	$479,025	
Fixed Assets				$10,535,200		
Inventories				$1,030,700		
Timber				$5,729		
Oil					$166,527	
Natural Gas					$138,209	
Coal					$155,678	
Minerals					$18,611	
Water					K0.sp.ec.h2o	
Economic Supply	$8,042,812	$507,100				
Economic Uses	$3,502,812	$364,000	$3,933,800	$749,300		
Product: GDP	$4,540,000	($143,100)	$3,933,800	$749,300		
Env. Protection	[28,172]					
Depreciation	$502,200			($502,200)		
Net Product: NDP	$4,037,800	($143,100)	$3,933,800	$247,108		
Environmental Uses						
Timber Harvests	$130			($130)		
Timber Net Growth	($159)			$159		
Oil Extraction	$17,793				($17,793)	
Oil Discoveries					$20,066	($20,066)
Nat. Gas Extraction	$11,617				($11,617)	
Nat. Gas Discoveries					$8,400	($8,400)
Coal Mining	$532				($532)	
Coal Discoveries					$0	$0
Mineral Extraction	$824				($824)	
Mineral Discoveries					$0	$0
Water Extraction	$10,869				($10,869)	
Water Returned	($7,877)				$7,877	
Net Product: EDP1	$4,00[illegible],071	($143,100)	$3,933,800	$247,129	$473,733	($28,466)

economic asset, by $3.2 billion. For coal and minerals no discoveries took place to of offset the depletion charges recorded in the calculation of EDP1.

The changes in water resources are characterized solely within the economic non-produced asset balances. This classification reflects the explicit judgement that water is a <u>controlled</u> resource rather than one that exists in the environment. This specification raises an important classification issue. To date, neither the applications of the SEEA nor the SEEA Handbook provides unambiguous guidance on how to classify a natural resource like water. The extent to which it exists in the economic or the environment realm is a question that environmental economics can aid national accountants in answering.

In closing this discussion of natural resource commodities, it is useful to emphasize that focusing on natural resource depletion provides an incomplete picture of the changing status of natural resource assets. This shortcoming applies as well to several past efforts to adjust GDP for natural resource_depletion. The calculation of EDP1 in SEEA does not complete the picture, since it ignores the discovery of non-produced natural assets (but not the production of natural resources like timber). Only in the SEEA asset balances, both economic and environmental, is there a complete picture of the overall change in wealth. In this respect, despite the classification issues raised earlier, the SEEA represents an improvement in the integration of economic and environmental perspectives for natural resource commodities.

Environmental Degradation, NDP Adjustments, and Asset Balances

In the larger scheme of things, the natural resource adjustments to NDP reflected in EDP1 were not that large. Environmental adjustments are more significant under this particular application of SEEA. EDP2, shown within the shaded area of Exhibit D, is the result of adjusting conventional NDP to reflect the costs of controlling residual pollution. The resulting estimate is $3.7 trillion, or 91% of conventional NDP. Since the unabated pollution is characterized as a loss of environmental assets, overall net capital formation is not only much smaller than under conventional economic accounting it is negative. This implies a decline in the overall capital (man-made and natural) of the U.S. There is a growth in produced assets of $247 billion a decline in economic non-produced assets of $5 billion, and a decline in environment non-produced assets of $328 billion summing to a decline of $86 billion. The decumulation of capital stock causes tremendous concern when ordinary capital is involved. If one accepts the definition of environmental assets as part of the capital stock from which we derive important goods and services, then this decumulation raises the possibility that something socially undesirable is occurring. Taking these estimates at face value, net manmade capital accumulation needed to be about 35% higher to avoid a loss in national wealth.

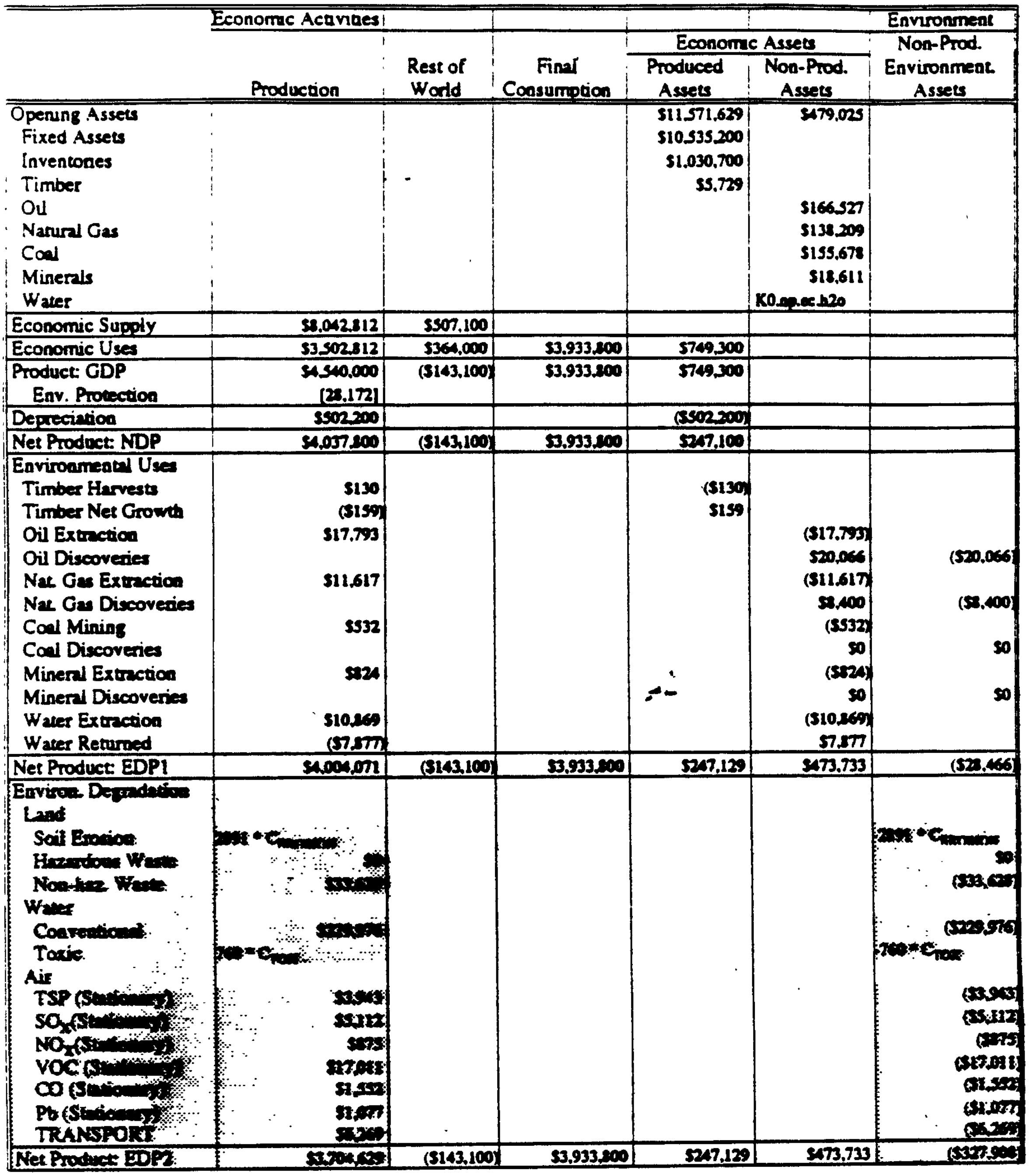
Calculation of EDP2

In this U.S. pilot study of SEEA the degradation of environmental resources is valued using a maintenance cost approach. For each of three environmental media (land, water, and air), the costs of controlling the existing level of pollution became the basis for adjusting NDP/EDP1 to derive EDP2. The level of assumed control is complete meaning that the aggregate maintenance costs presented here suggest the level of resources necessary to eliminate this pollution entirely.

This assumption may appear to be an extreme one. It does however illustrate the type of decision that anyone implementing this SEEA version has to make. The SEEA developers provide little definitive guidance on how to specify this parameter. In effect, it represents one's assumptions about the level of pollution with which no damages are associated. Environmental policymakers, much less national income accountants, would be hard pressed to make a clear decision, except possibly through the use of extensive modelling.

While the zero-pollution assumption may result in an unusually high estimate of the maintenance costs associated with the level of pollution in 1987, the estimated unit costs themselves tend to offset this tendency. For land and air pollution, unit costs were estimated using average costs of control experienced in the past. These costs would probably be lower than the marginal costs of controlling existing pollution. Water pollution may be the single but large exception. Unit costs of controlling conventional water pollutants were derived from recent surveys of wastewater

Exhibit D.
Environmental Accounts for the United States, 1987
Resource Depletion and Environmental Degradation
($ Millions)



	Economic Activities			Economic Assets		Environment
	Production	Rest of World	Final Consumption	Produced Assets	Non-Prod. Assets	Non-Prod. Environment. Assets
Opening Assets				$11,571,629	$479,025	
Fixed Assets				$10,535,200		
Inventories				$1,030,700		
Timber				$5,729		
Oil					$166,527	
Natural Gas					$138,209	
Coal					$155,678	
Minerals					$18,611	
Water					K0.np.ec.h2o	
Economic Supply	$8,042,812	$507,100				
Economic Uses	$3,502,812	$364,000	$3,933,800	$749,300		
Product: GDP	$4,540,000	($143,100)	$3,933,800	$749,300		
Env. Protection	[28,172]					
Depreciation	$502,200			($502,200)		
Net Product: NDP	$4,037,800	($143,100)	$3,933,800	$247,100		
Environmental Uses						
Timber Harvests	$130			($130)		
Timber Net Growth	($159)			$159		
Oil Extraction	$17,793				($17,793)	
Oil Discoveries					$20,066	($20,066)
Nat. Gas Extraction	$11,617				($11,617)	
Nat. Gas Discoveries					$8,400	($8,400)
Coal Mining	$532				($532)	
Coal Discoveries					$0	$0
Mineral Extraction	$824				($824)	
Mineral Discoveries					$0	$0
Water Extraction	$10,869				($10,869)	
Water Returned	($7,877)				$7,877	
Net Product: EDP1	$4,004,071	($143,100)	$3,933,800	$247,129	$473,733	($28,466)
Environ. Degradation						
Land						
Soil Erosion	2891 * C[illegible]					2891 * C[illegible]
Hazardous Waste	$0					$0
Non-haz. Waste	$33,628					($33,628)
Water						
Conventional	$229,976					($229,976)
Toxic	$760 * C_{TOXIC}$					$760 * C_{TOXIC}$
Air						
TSP (Stationary)	$3,943					($3,943)
SO_x (Stationary)	$5,112					($5,112)
NO_x (Stationary)	$875					($875)
VOC (Stationary)	$17,011					($17,011)
CO (Stationary)	$1,552					($1,552)
Pb (Stationary)	$1,077					($1,077)
TRANSPORT	$6,269					($6,269)
Net Product: EDP2	$3,704,629	($143,100)	$3,933,800	$247,129	$473,733	($327,908)

treatment costs by the National Research Council. These estimates approximate marginal costs better since they are based on current costs of constructing particular types of water treatment facilities.

Environmental damages were identified primarily through inventories of polluting residuals. An important consideration in constructing the SEEA system on a regular basis is the availability and reliability of these databases. Although most of the data were compiled from EPA data sources. there is still wide variability in the reliability and regularity in the collection of the source data. If a more routine implementation of the SEEA is envisioned, these data issues will need to be weighed in decisions about how the SEEA will be constructed and used.

The calculation of degradation costs for each of the three media are discussed briefly below.

Land

Three categories of degradation of land are considered: soil erosion, hazardous wastes, and "non-hazardous" wastes.

Estimates of soil erosion were derived from an inventory of rural lands by the Soil Conservation Service. No estimates of the maintenance costs were identified. For this mason, the entry is represented by the amount of soil erosion (million tons) times the hypothetical unit cost of mitigating the erosion.

Although this version of the SEEA does not permit its use, it was possible to derive an aggregate estimate of the off-site damages associated with soil erosion. This estimate was $14.3 billion, which indicates the amount that society would be willing to give up to control soil erosion. Under a different version of the SEEA that considers costs borne, this estimate could be used to adjust EDP2 by adjusting consumption in lieu of or in addition to production.

Hazardous wastes are for the purposes of this pilot study defined by federal regulations. Any wastes defined as hazardous must be managed in specific ways to protect the environment. Accordingly, it is assumed that hazardous wastes do not impose damage on the environment given the additional assumption of full compliance. Consequently, while the volume of hazardous wastes generated each year is very large (290 million tons in 1987), hazardous wastes do not affect the calculation of EDP2. The hazardous waste management expenditures are already reflected in the calculation of conventional GDP and NDP and in the estimate of value-added associated with the environmental protection industry highlighted above.

Just as hazardous wastes are defined by federal regulation by default so are non-hazardous wastes. These are wastes that do trot have to be managed according to federal hazardous waste regulations but which nonetheless may still pose a hazard or some other environmental impact. More than 8 billion tons of these wastes were generated, mostly from manufacturing. To estimate maintenance costs, it was assumed that the same level of care was necessary for these wastes as for hazardous wastes. To avoid any environmental impact, this assumption may not be too unreasonable since there are indivisibilities in the capital necessary to manage the wastes according to federal regulations (such as the requirement of liners in landfills). The actual unit costs applied to non-hazardous wastes reflects the incremental costs of going from the current level of expenditure on these wastes to what would be comparable for this volume of wastes if federal requirement were imposed. The resulting aggregate maintenance costs are $33.6 billion, accounting for about 10% of the adjustment for EDP2.

Water

Water pollution presented one of the most difficult challenges in calculating degradation. The difficulty stemmed primarily from the lack of reliable information on emissions of conventional or toxic pollutants. At the same time, the resulting estimate of aggregate maintenance costs were so large, accounting for 77% of the adjustment for EDP2. Together, these circumstances are cause for concern. Consequently this component of EDP2 should be viewed with considerable caution at this stage of development.

To construct a basic aggregate picture of the amount of conventional and toxic pollutants, it was necessary to use a variety of often irregular data sources. This approach posed significant obstacles to an independent verification of the estimated loadings. Ultimately, the physical measures of the majority of pollutants were not used directly (Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), nitrogen and toxics) in the estimation of maintenance costs. Only phosphorus emissions and their estimated control costs were used directly since their volume determined the number of facilities that needed to be constructed, assuming- that water pollution appears uniformly in the concentrations for which these facilities are designed.[6] Furthermore, given this same assumption for other pollutants, these same facilities would be sufficient in theory, to control BOD and 97% of nitrogen. TSS was so much larger in aggregate volume that this approach seemed inappropriate. As such, the estimated costs of $230 billion reflect the resources necessary to control phosphorus, BOD, and most of nitrogen under very special circumstances.

This approach to deriving a maintenance cost estimate is unsatisfactory because it applies a point-source means of control (wastewater treatment facilities) to a problem that sterns largely from non-point sources, which means that less costly ways to accomplish even a zero-pollution goal are likely. Ironically, this approach is also unsatisfactory because it may not satisfy the SEEA criterion of estimating the costs to reduce emissions to. a non-polluting level since TSS would not be eliminated. In this respect, the maintenance cost estimates may be too low. In practice, then, the implementation of SEEA with respect to water degradation had severe limitations in this U.S. application.

Nonetheless there may be some value in the experience. If even just a portion of the $230 billion degradation estimate proves realistic, then at least given a maintenance cost perspective, water degradation is likely to carry great weight within an SEEA system. For environmental economists, this may be a frightening prospect because it only reflects the cost side of the issue. Frightening, that is, unless the as yet unknown estimated damages are least equally large.

Air

Environmental degradation from air pollution may be the most straightforward of all the ones considered. EPA routinely collects or estimates statistics on the emissions of certain key pollutants. This SEEA example focuses on TSP, SOx, NOx, VOCs, carbon monoxide (CO), and lead (Pb). Toxic air pollutants represent a more recently considered phenomenon and are less well-tabulated.

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[6] The estimates of control costs per facility were obtained from the National Research Council (1993).

Unit costs were estimated using information from published EPA documents, a not-so-small indication that this information could be compiled on a routine basis to support the implementation of environmental accounts. The unit costs were derived by dividing the aggregate air pollution control expenditures in 1987 by the estimated emissions reduction attributable to these expenditures. For stationary sources, it was possible to use pollutant-specific expenditures in 1987, based on U.S. EPA (1990), as well as pollutant-specific reductions (U.S. EPA, 1989). Because joint control of pollutants is more common with mobile sources, pollutant-specific expenditures were not available. As a result, the total mobile source expenditures for air pollution control were divided by the sum of all mobile source pollutants (by weight). In Exhibit D, the row labeled TRANSPORT provides the relevant maintenance costs for mobile sources. Together, the stationary and mobile source pollutants account for approximately 10% of the EDP2 adjustment.

Environmental Degradation: Conclusion

In sum, the exercise of implementing the SEEA maintenance cost concept of degradation revealed several types of problems that should be considered more carefully before the results can be taken seriously - for the light they shed on economic-environmental interactions much less for any bearing they may have on economic or environmental policy. Nonetheless, these results do not detract completely from the general impression drawn from this exercise that environmental degradation poses a serious matter to be addressed by economic accounting. Even discounting the degradation results by an order of magnitude (to $30 billion), they still appear to be substantial, at least relative to the depletion estimates ($34 billion) and to current efforts to control pollution (measured by value-added of $28 billion from the environmental protection industry).

Exhibit E presents the complete, consolidated table of SEEA results from this pilot U.S. study. Nothing significant has been added. The final components which have been added are the revaluation rows, for which no data are provided, and the closing asset balances, which summarize changes presented in earlier discussions of asset changes. Note that no entries are provided in the closing balances or the opening balances of environment non-produced assets. The SEEA only calls for measuring changes in these assets not their total values. Omitting total values seems to be more of a concession to the substantial obstacles posed by estimation than a conclusion about the validity of the concept. The difficulty may not stem so much from the challenge of making a physical inventory of the environment. That is indeed possible for certain facets, such as the extent of old “growth forests. Instead a substantial part of difficulty comes from the challenge of valuation which as this application has shown, is already very hard when only marginal changes are involved.

Consolidated SEEA Results for the U.S.

Exhibit F presents several key statistics from this pilot SEEA application, some of which have already been cited above. At a glance, this presentation highlights two environmental phenomena that are worth further inquiry. One is that environmental depletion adjustments to NDP stand out far more than natural resource depletion adjustments. The second phenomenon is the apparent indication that in 1987, the U.S. appeared to be living beyond its means. There is an apparent decumulation of wealth as indicated by negative net capital formation as well as by the fact that the final consumption exceeds EDP2. If the current implementation were more than a pilot effort and if the economic accounts truly encompassed all capital, this particular finding could point to unsustainable tendencies in U.S. economic activities. As it is, this statistical result merely suggests that there may be tendencies that are worth worry about and investigating further.

Exhibit E.
Environmental Accounts for the United States 1987
Resource Depletion and Environmental Degradation
($ Millions)

	Economic Activities			Economic Assets		Environment
	Production	Rest of World	Final Consumption	Produced Assets	Non-Prod. Assets	Non-Prod. Environment. Assets
Opening Assets				$11,571,629	$479,025	
Fixed Assets				$10,535,200		
Inventories				$1,030,700		
Timber				$5,729		
Oil					$166,527	
Natural Gas					$138,209	
Coal					$155,678	
Minerals					$18,611	
Water					K0.np.ec.h2o	
Economic Supply	$8,042,812	$507,100				
Economic Uses	$3,502,812	$364,000	$3,933,800	$749,300		
Product: GDP	$4,540,000	($143,100)	$3,933,800	$749,300		
Env. Protection	[28,172]					
Depreciation	$502,200			($502,200)		
Net Product: NDP	$4,037,800	($143,100)	$3,933,800	$247,100		
Environmental Uses						
Timber Harvests	$130			($130)		
Timber Net Growth	($159)			$159		
Oil Extraction	$17,793				($17,793)	
Oil Discoveries					$20,066	($20,066)
Nat. Gas Extraction	$11,617				($11,617)	
Nat. Gas Discoveries					$8,400	($8,400)
Coal Mining	$532				($532)	
Coal Discoveries					$0	$0
Mineral Extraction	$824				($824)	
Mineral Discoveries					$0	$0
Water Extraction	$10,869				($10,869)	
Water Returned	($7,877)				$7,877	
Net Product: EDP1	$4,004,071	($143,100)	$3,933,800	$247,129	$473,733	($28,466)
Environ. Degradation						
Land						
Soil Erosion	2891 * $C_{EROSION}$					-2891 * $C_{EROSION}$
Hazardous Waste	$0					$0
Non-haz. Waste	$33,628					($33,628)
Water						
Conventional	$229,976					($229,976)
Toxic	760 * C_{TOX}					-760 * C_{TOX}
Air						
TSP (Stationary)	$3,943					($3,943)
SO_X (Stationary)	$5,112					($5,112)
NO_X (Stationary)	$875					($875)
VOC (Stationary)	$17,011					($17,011)
CO (Stationary)	$1,552					($1,552)
Pb (Stationary)	$1,077					($1,077)
TRANSPORT	$6,269					($6,269)
Net Product: EDP2	$3,704,629	($143,100)	$3,933,800	$247,129	$473,733	($327,908)
Revaluation						
Prod. Assets				Rev.p.ec		
Timber				$0		
Oil					$0	
Natural Gas					$0	
Coal					$0	
Minerals					$0	
Water					Rev.np.ec.h2o	
Closing Assets				$12,239,158	$473,733	
Fixed Assets				$11,143,400		
Inventories				$1,098,000		
Timber				$5,758		
Oil					$168,800	
Natural Gas					$134,992	
Coal					$155,146	
Minerals					$17,787	
Water					K1.np.ec.h2o	

Exhibit F

Comparison of Indicators Based on Conventional and on Environmental Measures

	Conventional Accounts	EDP1 (% of Conventional)	EDP2 (% of Conventional)
NDP	$4,037.8 billion	$4,004.1 billion (99.2%)	$3,704.6 billion (91 .7%)
Net Capital Formation	$247.1 billion	$213.3 billion	-$86.1
Net Capital Formation, as % of NDP or EDP	6.1%	5.3%	-2.3%
Consumption, as % of NDP or EDP	97%	98%	106%

Conclusions

We return to the three objectives of the SEEA stated at the outset of this paper to determine whether implementation of the SEEA is appropriate and useful for the U.S. They are to: 1) provide an accounting of the interaction of the economy and the natural environment, 2) address sustainable development concerns through proper accounting of both manmade and natural assets, and 3) develop environmentally adjusted measures of GDP to serve as a guide toward sustainable development. Since it seems reasonable to assume that these objectives are ones generally shared by our society, we review each as the means of answering this question.

The SEEA does provide a means for better accounting of the interaction of the economy and the natural environment, in at least two special ways. First, SEEA is far more complete in showing ways that the economy can infringe on the environment and how the environment contributes to the economy than the SNA ever was. When one starts with an accounting system that is so thoroughly oriented to market transactions and production it is quite an achievement to flesh out a system that maintains consistency with economic accounting while incorporating the environment. Through the progression of various versions of SEEA, it is possible to see, as shown in the paper, the concepts of environmental depletion and degradation transformed from alien concepts that are almost completely excluded or ignored in conventional accounting to ones that are full-fledged elements of an accounting framework that actually uses non-market values. Whether national accountants ever go that far may depend on how much environmental economists get involved in the process, an issue to which we return below.

The second special way that SEEA provides a better means for depicting environment-economic interactions is its recognition of natural capital as a legitimate component of a nation's asset balances. Although this step is a long way from making it possible to track the sustainability of a nation's wealth. it is a necessary step. Until natural capital is scrutinized in tandem with manmade capital, economic accounting will be biased against the preservation of natural capital, While the pilot study in this paper has demonstrated in a limited way the magnitude of the difficulties in reliably implementing a system of manmade and natural capital accounting, these difficulties do not remove the appeal of putting natural and manmade capital on even terms.

This point relates to the second objective of SEEA. Whether better natural capital accounting can help address sustainable development concerns will depend on how well natural capital is actually understood. Consequently, whether SEEA is right for the U.S. does not depend solely on the structure of SEEA itself. SEEA depends critically on the information which it incorporates. It should be emphasized that SEEA incorporates the environment less than it opens up the accounting system to better information on linkages between the economy and the environment. In many ways, SEEA can be seen as a user of environment-economic information rather than as a generator. For example, the maintenance cost approach demonstrated in this paper depends on judgments of the non-damaging levels of pollution. National accountants cannot be the arbiters of such choices. Instead environmental economist, public health specialists, ecologists, and others could be. This circumstance presents an opportunity for environmental economists. SEEA is like an empty vessel. It is good enough to use a lot of information that has not yet been fully developed. Any improvements in understanding the relationships between the environment and the economy can be incorporated in the SEEA system.

Promising as such developments seem to be, the number of unanswered questions about the relationship between the environment and the economy is very large. This predicament brings us to the third objective of SEEA - to develop environmentally adjusted measures of GDP as guidance for sustainable development. If the characterizations of natural capital and of environmental goods and services are still so limited how good can any resulting "green GDP" measures be that incorporate them? We suspect that they may indeed be inadequate but, in the face of GDP measures which turn an even blinder eye to the environment, we also suspect that improved knowledge lies in the direction of environmental accounting and not toward past conventions.

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Intergenerational Welfare Economics and Environmental Policy

by

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Paper Presented at the Association of Environmental and
Resource Economists Workshop,
“Integrating the Environment and the Economy: Sustainable
Development and Economic/Ecological Modeling,”

Boulder, Colorado, May 5-6, 1994.

Intergenerational Welfare Economics and Environmental Policy[1]

by

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The central "story" of environmental economics is now well established. Market economies do not, through the unaided guidance of the invisible hand, achieve economic efficiency in the allocation of many environmental resources. Causes of market failures include externalities, the public good characteristics of some environmental services, and property rights problems such as open access. Much has been accomplished by prescribing policies to reduce market failures. Nevertheless, one must ask whether market-failure based approaches adequately capture the full extent of the environmental issues facing the world today. Are global warming, worldwide erosion of soils, contamination of groundwater, losses of biological diversity, destruction of wetlands, overfishing, ozone depletion, rapid exhaustion of nonrenewable resources, and other such issues only of economic interest when they result from market failures? In this paper, we argue that defining environmental problems and their solutions within the market-efficiency framework misses the crux of many of today's environmental problems. A more complete environmental economics would be based on the dual goals of efficiency and sustainability.

We define an economy as sustainable if each successive generation has per capita economic opportunities at least as large as those enjoyed by earlier generations. By focusing on "opportunities" rather than "welfare" or "income," this definition places conditions upon initial endowments that each

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generation should receive. Endowments are broadly defined to include not only natural resources but also the capital, infrastructure, technology, knowledge and institutions that today's generation will pass onto its children.

In the first major section of this paper, we discuss the implications for welfare economics of including sustainability as well as efficiency. To accomplish this, three intergenerational theoretical models are developed. Following Page (1977), the first two are dubbed the “Hardtack World” and the “Corn World.” In the Hardtack World, a finite number of generations divide a single, non-renewable resource. In the Corn World, an unlimited number of generations exploit a renewable resource. Finally, we add a world with capital. The problem there is like the hardtack problem but capital formation (and hence technological progress) are possible. Here, output is produced using a non-renewable resource and capital. The output in each period can either be consumed or invested. Accumulated capital is productive in later periods and can be substituted, up to a point at least for diminished stocks of the resource as time progresses.

Though these cases are abstract and highly stylized, they serve to illustrate how a basic result of welfare theory carries over to the intergenerational world. Based on the familiar Edgeworth box diagrams, any Pareto efficient state of the economy rests on a foundation of initial endowments held by economic actors. However, as is well known, an infinite number of Pareto efficient states are possible, each based on a different allocation of initial endowments. While the Edgeworth box itself must be discarded in favor of a more dynamic representation of the economy, this basic conclusion carries over to a world with time and more than one generation. The result is an infinite number of possible efficient time paths for an economy, each depending on a different intergenerational allocation of endowments. In each of the cases we consider, there are many efficient time paths. Along any of these, it is impossible to make members of one generation better off without harming members of another. An important conclusion follows: While there are an infinite number of possible Pareto-efficient time paths, only a subset of those efficient paths are also sustainable. Achieving efficiency does not guarantee sustainability. Rather, if society wishes to be both efficient and sustainable, the quest for economic efficiency must be carried out within what we shall term “sustainability constraints.”

We then discuss how the principles of sustainability might be applied in a real world context. First, we address the basic question of whether sustainability should be a goal of economic analysis or not. Given the great public interest in sustainability and global environmental issues, it is our conclusion that economists would be remiss if we left such an important issue aside. A number of important complications arise in putting sustainability concepts to work. Most of all, the uncertainty associated with long-term environmental and economic issues makes determining if a particular path is truly sustainable difficult if not impossible. Uncertainty, even ignorance, of the long-term ramifications of our actions, make planning for efficiency and sustainability a very inexact task. Faced with this uncertainty, we discuss two policy options designed to push the economy towards both sustainability and efficiency.

EFFICIENCY AND SUSTAINABILITY IN THEORY

In this section we develop three simple models to discuss the fundamental issues of incorporating sustainability into the framework of welfare economics. We will demonstrate the importance of establishing constraints on the economy if society is to ensure that sustainability is achieved. While the framework presented here is far from general, we believe that extensions of the model can be developed to form policies for real economies that have a multitude of endowments and outputs. We start, however, with the most simple case.

The Hardtack World[3]

What we need to explore the welfare economics of intergenerational resource use is the dynamic analogue of an Edgeworth box diagram. Our simplest model elaborates a bit on an argument of Norgaard (1991). Figure 1 illustrates the principles involved. In order to focus on very fundamental issues, this figure takes the simplest possible intergenerational case: an economic universe consisting of only two non-overlapping generations with equal populations that exploit a single, non-renewable resource. It is as if “society” for purposes of welfare analysis consists of two separate groups of people who will be

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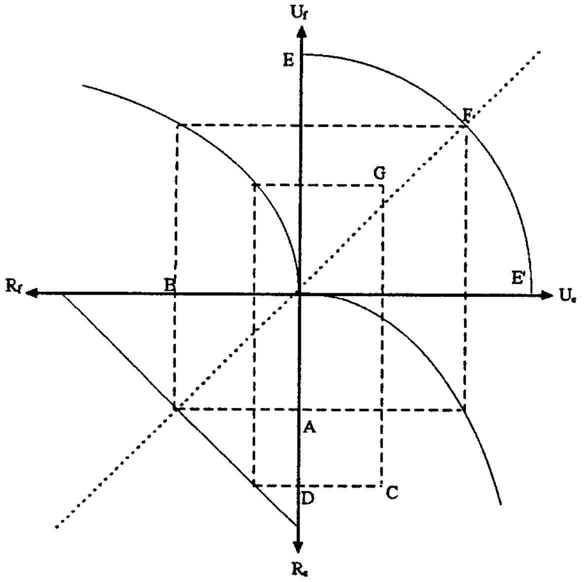
[3] This section draws heavily on Richard C. Bishop and Richard T. Woodward, “Efficiency and Sustainability in Imperfect Market Systems,” Oregon State University, Graduate Faculty in Economics, Public Lecture Series, Forthcoming.

marooned on a desert island during non-overlapping time periods and only the first generation will have provisions, composed of a fixed supply of hardtack. The first group must decide how much hardtack to eat and how much to leave for the second group. We assume that capital per se does not exist and that there is no technological progress.

Figure 1



The per capita utility of the future generation, **U_f,** is measured by the vertical axis above the origin. Likewise the current generation's utility, **U_c,** is measured along on the horizontal axis to the right of the origin. Positive utility is assumed to be possible only when resources are consumed in positive quantities. Each point in the graph's northeast quadrant, then, represents a time path of per capita utility and points along the curve connecting points E and E' thus represents the efficiency frontier for this very simple **world.**[4]

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[4] We assume that the we assume that levels of utility are directly comparable across generations and that wealth within each generation is distributed according to that generation's social preferences. Obviously we are suppressing very important issues here, not the least of which is that Arrow (1963) has shown that a social ordering which adheres to a few simple rules is impossible.

The other quadrants in the figure help illustrate the derivation of EE'. The allocation of the resource between the generations is depicted in the southwest quadrant by the constraint with a slope of -1 to reflect its nonrenewable nature. From a slightly different perspective, the constraint pictured in the southwest quadrant shows the alternative time paths for intergenerational resource endowments. The curves in the southeast and northwest quadrants show the maximum levels of per capita utility that can be achieved by the current generation and the future generation, respectively, as a function of resource consumption. The intragenerational utility functions are assumed to be monotonically increasing in consumption and concave.

The point in the north-east quadrant that is actually reached depends upon two factors: the efficiency with which each generation uses the resource, and the distribution of the resource between the two generations. For example, if the current generation uses resources at point A, where the available resource is divided equally, and both generations behave efficiently, then per capita utility is F for both generations. If the current generation uses more than A, there will be so little of the resource left that the future generation will not be able to achieve a per capita utility level equal to that available to the current generation.

Sustainability can be simply defined in the fully efficient case. It would be achieved if the future generation achieves a level of per capita utility at least equal to that of the current generation. This criterion is met here if the current generation uses no more than A of the resource, so that the per capita resource stock available to the future generation is at least as great as that used by the current generation. In a fully efficient economy, therefore, sustainability can be defined either in terms of the distribution of endowments or in terms of outcomes.

The situation becomes slightly more complex if the possibility of intragenerational inefficiency is admitted. Suppose that the current generation does not achieve efficiency, say because it has a market economy and market failures are allowed to persist. Then it will enjoy some level of per capita utility below its utility frontier. Suppose, as a specific case, that it uses D of the resource, but only achieves level C of per capita utility. This would allow the future generation to achieve only G at a maximum. Since, at G, the future generation's well-being exceeds that of the present, should we say that the current generation acted in a manner consistent with sustainability? Surely the answer must be "no." As point G makes clear, in a world with economic imperfections, it is not satisfactory to define sustainability in terms of levels of utility. While at G the future generation achieves a higher level of utility than the current generation, this is true only because of the inefficiencies of the current generation. We see in this simple example the importance of defining sustainability in terms of endowments, in this case the initial division of the resource stock. Our simple economy will be sustainable only if resource consumption by the current generation is less than or equal to A.

Interestingly, our analysis indicates that efficiency and sustainability need not be conflicting goals. We have demonstrated in the case of two generations and one-dimensional endowments that a subset of the infinite number of efficient paths is also sustainable. The dual goals of efficiency and sustainability could be pursued by treating sustainability as a constraint. A society holding both goals would constrain itself to considering only those efficient paths that are also sustainable. In the simple world of Figure 1, the sustainability constraint can be simply stated.

$$\text{Sustainability constraint} \quad R_c \leq \frac{S_0}{2}$$

where S_0 is the initial level of the resource. It is straightforward to extend this model to an economy with n generations. In this case the sustainability constraint for generation g would be given by

$$\text{Sustainability Constraint:} \quad R_g \leq \frac{S_g}{n-g+1}$$

Even with a large number of generations, it is possible to seek a path that is both efficient and sustainable. While we must examine this conclusion in more complex models, there is no obvious reason to believe this basic principle would not apply there as well.[5]

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[5] We should candidly admit right here near the beginning that this issue has not been thoroughly explored in a rigorous fashion. Howarth and Norgaard (1990) and Howarth (1991) have made important beginnings. Their basic approach, however, is to assume a social welfare function and then investigate its implications for resource endowments. From our perspective, the dynamic equivalent of an Edgeworth box would be more useful in defining necessary and sufficient conditions for an efficient and sustainable equilibrium. Considerable progress has been made on growth models with overlapping generations (see, for example, Fisher 1992) but to our knowledge such models have yet to included natural resources.

Of course, the Hardtack World has tremendous limitations. It is not fully satisfactory as a model of sustainability for many reasons, not the least of which is its rather dim view of long run prospects. So long as the only resource is non-renewable and capital accumulation and technological progress are ruled out by assumption, sustainability over the indefinite future is infeasible. As the number of generations increases without limit the sustainability constraint will approach a restriction that none of the resource be used. Once a renewable resource is introduced, however, this difficulty disappears. Thus, we move from the Hardtack World to the Corn World.

Efficiency and Sustainability in the Corn World

Let us again consider an economy of non-overlapping generations, Instead of bringing a box of hardtack like in the preceding model, the resource is a renewable resource, say corn, where the g^{th} generation inherits an initial endowment of seed totaling S_g. The initial endowment of corn can either be consumed or planted. We presume growth rates are constant for each seed planted so that technology is constant returns to scale. Each pound of corn will result in a harvest of 1 + r units of corn at the end of a growing season. We shall assume that each generation lives for one growing season so that the corn available at the end of the growing season becomes the inheritance of the next generation. To be efficient all the corn available to each generation g, must either be planted or consumed, none can be lost. To be sustainable, each generation must plant enough corn, measured as I_g, so as to satisfy

$$\text{Sustainability constraint} \quad I_g \geq \frac{S_g}{1+r}$$

If this constraint is just satisfied, each generation will inherit an endowment of at least S_g so that the opportunities available to the next generation are identical to generation g. If generation g satisfies the sustainability constraint and is also fully efficient, they will be able to consume

$$C_g = \frac{rS_g}{1+r}.$$

Notice that economic growth is possible in the corn economy. Earlier generations could plant more than the minimum required by the sustainability constraint and enhance consumption possibilities for later generations. Later generations could in turn ratchet up the sustainability constraint from the initial level.

This is, of course, a much brighter world than the hardtack world provided that the initial endowment of corn is adequate. An indefinite number of generations could be supported at the minimal level set when the first generation arrives or at some higher level if the growth occurs. Furthermore, the corn world is easily interpreted within a welfare theoretical framework. An infinite number of Pareto efficient time paths exist. The only requirement is for Pareto efficiency is the one that has already been stated: each generation must either consume or plant all the corn at its disposal. Then, it would be impossible to reallocate corn among the generations to make members of one generation better off without simultaneously making some members of another generation worse off. Some of these time paths would be heavily skewed in favor of consumption by earlier generations; others would be more egalitarian; and still others would be skewed in favor of consumption by later generations. Still others might have rising and falling consumption across the generations. By adopting a sustainability goal, society chooses to limit itself to the subset of efficient paths that satisfy the sustainability constraint.

Before we begin to try to ferret out conclusions for policy from all this, one more world will be visited. It is like the hardtack world in that it depends to some extent on a non-renewable resource, but investment in productive capital will be possible.

Sustainability in an Economy with Resources and Capital

In the corn and hardtack economies discussed above, the endowment of each generation was limited to a single resource. We now consider the meaning of sustainability in economies with a two-dimensional endowment, consisting of a resource component, S, and a capital component, K. Some extensions to higher dimensions will be suggested but not fully developed. The basic idea, however, remains the same whether we are considering a one-dimensional or an n-dimensional endowment. The sustainability constraint will restrict economic activities to ensure non-decreasing economic opportunities.

In production each generation g uses up part of its stock of resources, $\mathbf{R_g}$, leaving the next generation with $\mathbf{S_{g+1}} = \mathbf{S_g} - \mathbf{R_g}$. The resources are used as inputs into a general production function $\mathbf{f(K_g, R_g)}$ which is increasing and concave in both terms. The total output, $\mathbf{f(K_g, R_g)}$, is either invested in capital, $\mathbf{I_g}$, or a consumed, $\mathbf{C_g}$, so that $\mathbf{K_{g+1}} = \mathbf{K_g} + \mathbf{[f(K_g\ R_g) - C_g]}$. The capital stock is presumed to not depreciate and, once created, cannot be consumed but only used as an input into the production process. The population is again assumed to be constant, generations do not overlap and the total number of generations is finite. The implications for an economy with an infinite number of generations will be discussed below.

Since each generation's welfare is solely a function of consumption, generation g is acting sustainably if, after producing and consuming, it leaves an endowment of capital and resources sufficient for all succeeding generations to consume at the level that generation g could have consumed by being both efficient and sustainable. As an intermediate step, we define the sustainability set, $O_g(C_0)$, as the set of all endowment pairs, (K_g,S_g), which are sufficient to allow generations g, g+1,...,T to consume at least C_0. This set can be expressed in symbols as

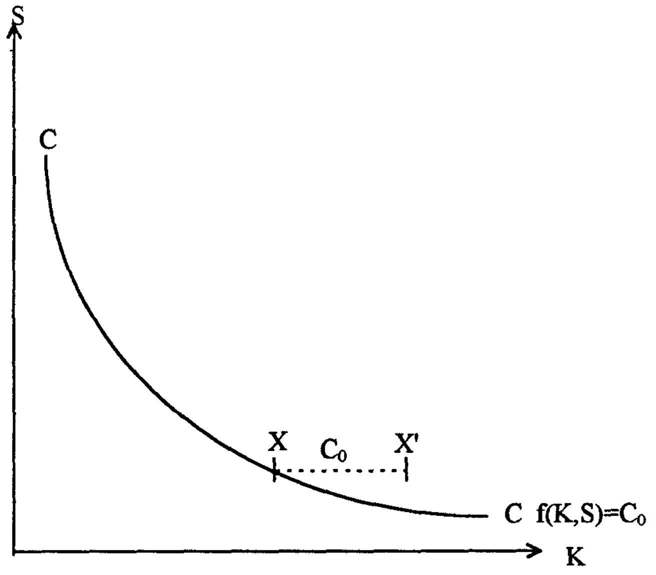
$$O_g(C_0) = \{(K_g,S_g) : \exists\, R_g>0: K_g + f\,(K_g,R_g)-C_0=K_{g+1},\ S_g-R_g=S_{g+1},\ (K_{g+1},\ S_{g+1})\in O_{g+1}(C_0)\}.$$

The frontier of this set is the sustainability constraint, $\overline{O}_g\,(C_0)$. There exists a maximum level of sustainable consumption C^*, which is the greatest level of sustainable consumption given the available resources. The actual endowment of the g^{th} generation (K_g,S_g), lies on the sustainability constraint associated with C^*, $\overline{O}_g\,(C^*)$.

Derivation of a two dimensional sustainability constraint

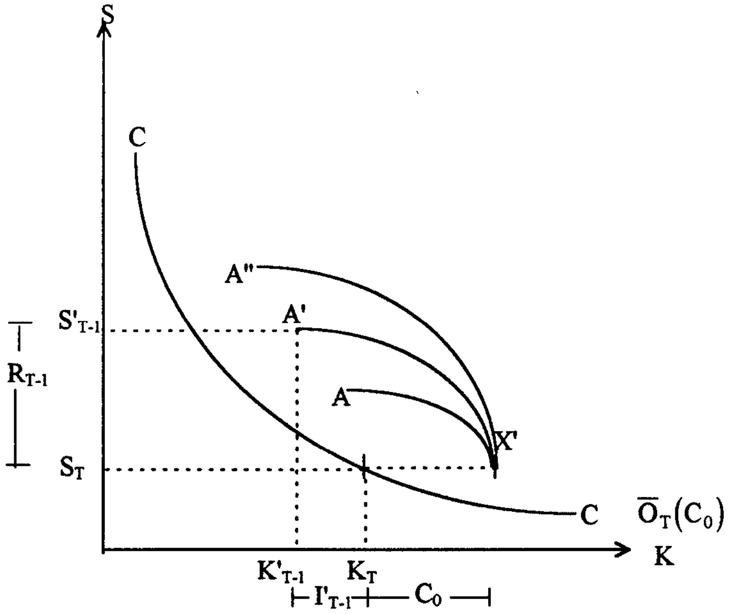
The sustainability constraint in the capital-resource economy is derived using backward induction. Consider the last generation in a T generation world. The last generation will, presumably, use up all remaining resources and not invest in capital so that, if they are efficienct, $C_T=f(K_T,S_T)$. The last generation's sustainability constraint associated with a consumption level C_0 is the set of all capital-resource endowments that will allow it to exactly produce C_0. This constraint, CC in Figure 2, is simply an isoquant. If the endowment pair inherited by generation T lies anywhere above CC, then it will have more than enough total resources to produce C_0. If it receives an endowment that falls below the constraint, then it will not be able to produce C_0.

FIGURE 2



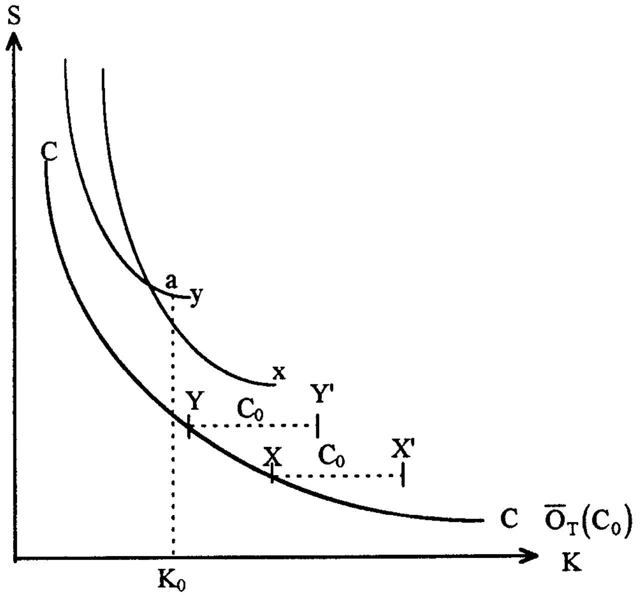
The next step is to derive the sustainability constraint for the second to last generation. Consider a point on CC, say X in Figure 2. If generation T is going to receive the endowment X, then generation T-1 will have to produce a level of output such that it is able to consume C_0 and still leave generation T at X. Since output, prior to choosing a level of consumption, can be used either for capital formation or consumption, generation T-1 must have an endowment sufficiently large to reach X' in Figure 2.

Figure 3



In Figure 3 three possible endowments A, A' and A" are indicated, all of which would be sufficient to allow generation T-1 to reach X'. Take point A', for example, where generation T-1's endowment is (K'_{T-1}, S'_{T-1}). By using R_{T-1} of the resource, and taking advantage of its endowment of capital, K'_{T-1}, generation T-1 could produce a total output of $I_{T-1}+C_0$. The curve connecting A' and X' is a production possibility frontier indicating the total output that can be produced at different levels of resource use. The production frontier is concave because as more resource stock is used up (movement vertically downward), the marginal increase in output declines. To reach X' from A, generation T-1 would have to use R_{T-1}. Because additional capital increases the marginal productivity of the resource, endowments with more capital stock, like A, would require less resource use to reach X'. Endowments with less capital stock, like A", would require more resource use to reach X'.

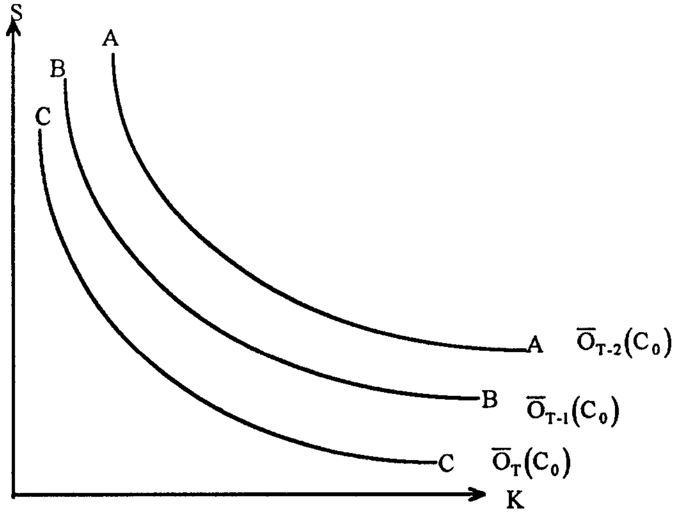
Figure 4



For each point like X, on the T^{th} generation's sustainability constraint, therefore, there are a multitude of possible endowments for the preceding generation that would allow it to consume C_0 and still leave generation T at X. By joining all the feasible endowments associated with X, we obtain a locus of points labeled with a small x in Figure 4. We then repeat the same operation for another point, Y, and obtain another locus, y in Figure 4. All the points on each of these two loci indicate endowments that would allow sustainable consumption of C_0 by generation T-1.

Consider two points along the feasible set of points x and y at a given level of capital K_0. Since either of these two points lead to the same level of consumption in generation T, the upper point, on they locus, indicated with an a is more than sustainable. That is, if the endowment inherited by generation T-1 were at a, then generation T-1 could produce enough to pass on a sustainable endowment to generation T and consume more than C_0. Hence point a lies above $\overline{O}_{T-1}(C_0)$. If we derived loci of sustainable endowments similar to x and y for every point on CC, the outer envelope of these curves would be the sustainability constraint for the $T\text{-}1^{th}$ generation $\overline{O}_{T-1}(C_0)$.

Figure 5



The resulting sustainability constraint for generation T-1 can then be traced out and would take a form like BB in Figure 5. Following the same procedure, the sustainability constraint for generation T-2 could also be traced out and would look something like AA. Repeating this process over and over again, the sustainability constraint of the g^{th} generation, $\overline{O}_g(C_0)$, is found. This locus would be the set of minimum endowments that generation g would need in order to consume C_0 and still leave an endowment of capital and resources so that generation g+1 and all following generations can also consume C_0.

Once $\overline{O}_g(C_0)$ is found, we can compare the actual endowment, (K_g,S_g), with the sustainability constraint. If we find that the g^{th} generation's endowment lies above $\overline{O}_g(C_0)$, then a C_0 is not optimal, a higher level of consumption could be sustainably consumed. If we find that the actual endowment lies below $\overline{O}_g(C_0)$, then C_0 is not sustainable and a lower level of consumption must be considered. In an iterative fashion it would be possible to determine the level of consumption C^* such that the g^{th} generation's endowment lies on $\overline{O}_g(C^*)$.

Extensions and generalizations of the multi-dimensional sustainability constraint

A number of extensions of the above analysis are worth pointing out. First, we can make some inferences about the economy as we relax the assumptions of finite generations. Much like the hardtack world above, the world that we have been discussing here may not allow sustainable positive levels of consumption if the number of generations is infinite. One way to state this is that for any positive level of consumption C_0, any finite endowment (K, S) will become unsustainable (fall below the sustainability constraint) in some finite number of generations, T^*. If, for example, the production function $f(\cdot)$ is CES with an elasticity of substitution less than one[6], then the average product of a unit of resource is bounded from above, making it impossible infinitely sustain a positive level of output (Dasgupta and Heal, 1979).

If the resource is more like that of the corn economy, such that if there is any positive resource stock $\underline{S}$, a level of resource $\underline{R}($ $\underline{S}$ can be used without diminishing the resource endowment of the following generation, then sustainability can be achieved even with an infinite number of generations. In this case the sustainability constraint associated with any finite level of consumption will converge to a single locus so that $\overline{O}_g (C_0) = \overline{O}_{g+k} (C_0) = \overline{O} (C_0)$ for all finite k.[7] This capital-corn economy simplifies the analysis in many ways since if generation g can determine the sustainability constraint on which its endowment lies, it can determine whether its actions are sustainable by evaluating if the endowment it passes onto generation g+1 lies on the same constraint. This property is used to analyze indicators of sustainability in Appendix A.

While we have considered only a two-dimensional endowment, the endowment vector could in principle be extended to a third or higher order vector. The number of calculations involved in

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[6] A constant elasticity of substitution (CES) production function in K and R is of the form

$$f(K,R) = \left[\alpha_1 K^{(\sigma-1)/\sigma} + \alpha_2 R^{(\sigma-1)/\sigma} + (1-\alpha_1-\alpha_2)\right]^{\sigma/(\sigma-1)}$$

$$\alpha_{1,}\alpha_2, 1-\alpha_1-\alpha_2>0 \text{ and } \sigma>0, \sigma\neq 1.$$

where σ is the elasticity of substitution between K and R If $\sigma = 1$, and $\alpha_1 + \alpha_2 = 1$, then $f(K,R)$ is Cobb-Douglas

[7] This can be seen by noting that if the g^{th} generation inherits (S_g, K), then passing on the same endowment to the next generation would clearly be sustainable, though this might not be optimal. Nonetheless, for any $\underline{R}>0$ and $\underline{C}>0$, there is a level of capital, $\underline{K}$ such that $f(\underline{K},\underline{R})=\underline{C}$. So, for all resource levels S that yield a positive recharge, R, we know that there is a capital level sufficiently high to support any consumption level without diminishing the resource stock. Hence, there is an upper bound on the sustainability constraint, composed of levels of K and S which can produce C_0 without diminishing the resource stock. Because this upper bound to the sustainability constraint exists, it must be the case that a single constraint exists at or below this upper bound.

calculating such a frontier, however grows exponentially. Hence, the properties of the n-dimensional sustainability constraint are not explored in this paper.

SUSTAINABILITY IN PRACTICE: FROM THEORY TO POLICY

There are several lessons from the above theoretical models that we will draw on to discuss the implications of sustainability for economic policy. First and foremost, in each of the models we showed that to ensure that sustainability is achieved, policy makers must consider the joint objectives of economic efficiency and sustainability. This may at first appear to be an obvious extension of the Second Welfare Theorem, and in a sense it is. Yet, when we consider intertemporal problems, as some examples below will show, very often economists voice only efficiency concerns when sustainability seems to be the central issue.

Secondly, we find that substitution and replenishment are both sources of sustainability in the long run. In the corn economy, sustainability required that each generation consumed no more than the recharge to the resource stock. In the capital-resource economy sustainability could be achieved if attention is given to the degree to which substitution is possible given the economy's productive capacity. Here too, however, sustainability will not be guaranteed unless the economy operates within the bounds defined by the sustainability constraint.

Finally, up to a point, sustainability can be achieved through substitution. As we see in the capital-resource economy in which substitutability is possible, sustainability does not require that the resource endowment passed from one generation to another be constant. Unless a particular resource is both essential and non-renewable, a policy that leads to the reduction of that resource is not necessarily unsustainable. However, unless specific measures are taken to increase other dimensions of the endowment vector, policies that have the effect of diminishing the resources being passed on to future generations will threaten sustainability. Here we see that our uncertainty makes defining policies that pursue both sustainability and efficiency particular troubling. Accurate knowledge of the sustainability constraint is never available. One policy intended to move the economy towards sustainability despite our enormous uncertainty is discussed below. We turn now, however, to a more fundamental question.

Should Sustainability Be An Economic Goal?

Advocating sustainability as a policy goal will be viewed with uneasiness by many economists because of their strong propensity to avoid expressing views on what is fair and what is not. The widespread interest that sustainability is generating among policy makers, environmental scientists, and the general public is reason enough to assume, for the remainder of this paper, that making economies sustainable is a worthy policy goal. We propose to conduct an economic discussion on a "what if" basis: What if sustainability were a goal of economic policy? What would the implications be for environmental economics? Our case for arguing that this is a meaningful exercise for economists to participate in is strengthened by the result that efficiency and sustainability need not be conflicting goals. It should be possible to seek a path that is both efficient and sustainable. Proposed steps that are viewed by their advocates as promoting sustainability will also have implications for efficiency. As a result, economists are being drawn into the debate.

As long as we are dealing with potential qualms of our economic colleagues, a second question also deserves attention. Some economists who will grant that sustainability is the potentially interesting from a theoretical perspective may still argue that the concept is irrelevant to policy, since economic growth can be expected to continue into the indefinite future. In the context of sustainability, economic growth in excess of growth rates in population implies ever expanding economic opportunities for successive generations. Witness for example, Beckerman's (1992) statement in the context of the debate over policies to address global warming,

> to give priority to highly speculative global environmental issues in general and to global warming in particular, in the interests of future generations who are likely to be far richer than we are today, and to take drastic action in pursuit of this goal, however costly it may be in terms of current living standards, would represent an unjustified sacrifice of the clearly apparent interests of billions of very poor people today.

In the context of this paper, such statements maybe interpreted as arguing that the sustainability constraint is not binding. Let us consider this view further using the concept of evolving intergenerational endowments.

A look at the relationship between economies and nature makes it hard to escape the feeling that future generations are in a vulnerable position. Each generation tends to treat as its endowment virtually all the natural resources that it has the technological and economic means to exploit. Historically, resource depletion and degradation were limited by technology, labor, and capital constraints. Exploitation of natural resources on the scale that is feasible today was impossible. The current generation, in contrast, is using non-renewable resources at an unparalleled rate. Furthermore, renewable resources are being more and more heavily exploited and degraded on a global scale. There can be little doubt that future generations will inherit natural resource endowments that are much reduced and much degraded.[8]

Societies have historically augmented their natural resource endowments through conquest and exploration to offset the depletion and degradation of their resources. Certainly, augmentation of resource endowments will continue to occur, but diminishing returns to efforts in this direction maybe felt. No more continents filled with nearly virgin resources are available. One has to wonder, for example, how many more oil producing areas with reserves as large as the Middle-East or even Alaska's North Slope are available for discovery.

With natural resource and environmental endowments declining, sustainability, if it can be achieved at all, will depend on increasing non-resource components of the endowment that future generations will receive. Just as capital can be augmented to makeup for reductions in the resource stock in the simple economy above, in the real world non-resource components are augmented by processes that we shall refer to collectively as “social progress”. Progress takes many forms: scientific and technological innovations, improvements in institutions, increases in cultural items (e.g., art and music), and human and physical capital accumulation. Social progress creates substitution possibilities, reducing or overcoming the ill-effects of declines in the natural resource endowments. Institutions, such as those associated with markets, can also play a role, creating incentives for both substitution and social progress.

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[8] Of course, much can be done to reduce resource depletion and degradation. Still, the point is that human life as it exists at the current time, appears to be incompatible with increasing or even constant future resource endowments. Recycling, pollution control, and other approaches are less than perfectly effective in stemming the tide of depletion and degradation.

In recent decades and centuries, social progress and resource augmentation in many countries have been more than adequate. The result has been expanding per capita economic opportunities. Despite reductions in the resource stock, these nations have apparently not violated their sustainability constraint. Though this is encouraging, sufficient social progress to allow continued growth in per capita economic opportunities may not be automatic.

Those who followed the “Growth Debate” of the 1970s no doubt find all this familiar. There, systems scientists and economists debated the prospects for further economic growth.[9] One can recast the conclusions of systems scientists into today's language by saying that they concluded that then-current economic trends were not sustainable. Economists responded by suggesting that the models developed by systems scientists were woefully inadequate in portraying the possibilities for social progress and resource augmentation. The Sustainability Debate of the 1990s has its own nuances, but it is fundamentally a continuation of the Growth Debate of the 1970s, which in turn can be traced back at least to Malthus.

We do not propose to resolve this debate here. Rather, these are issues about which sensible people ought to agree to disagree. Those who argue that the current economy is not sustainable ought to admit that they could be wrong, Perhaps social progress will be adequate to counterbalance depletion and degradation of natural resource endowments for the foreseeable future. And, those who have more confidence in social progress should admit that the economy could possibly be on an unsustainable path. Neither theoretical economic arguments nor empirical evidence are sufficient to justify a definite conclusion about the sustainability of the time paths on which the earth's economies find themselves. Accordingly, an investigation of the economic implications of combining efficiency and sustainability goals could have substantial policy relevance.

Uncertainty

An undercurrent in what has just been said about the Sustainability Debate now needs to be made explicit: Implementation of the concept of sustainability constraints in actual policies would have to

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[9] Relevant literature is summarized in Hartwick and Olewiler (1986), Chapter 6.

be attempted in a world of extreme uncertainty. Our theoretical efforts here have been conducted under the assumption of perfect knowledge. In fact, we of the current generation are quite ignorant about how our use of environmental and other natural resources will affect the economic prospects of future generations. As has already been emphasized, it is not clear whether the sustainability constraint is even binding. Earlier generations have a limited basis for judging which resources can be exhausted and degraded with little or no harm to later generations and which might be extremely valuable. Furthermore, the nature of the trade-offs between environmental resource components of the endowment vector and non-resource components are difficult to anticipate. Producing human and physical capital; science and technology; art, music, and literature; and even social institutions requires that we of the current generation use natural resources. In any given case, it is difficult to predict whether future generations will be better off in terms of economic opportunities with more environmental resources or with more social progress to augment their non-resource endowments. Alternative endowment vectors (including various levels of natural resource and non-resource components) have highly uncertain potential economic implications.

The uncertainty associated with these decisions is of an extreme kind, which for convenience, we might term "ignorance."[10] If we think in traditional terms, "risk" is used to characterize situations where more than one future outcome is possible and where all outcomes are known in terms of their payoffs and probabilities. "Uncertainty," in the traditional terminology, involves situations with more than one possible outcome, where payoffs are known, but probabilities are completely unknown. Neither of these constructs seems quite appropriate here, Under "ignorance," as we shall use that term, not all possible outcomes are known and payoffs from known outcomes are not always clear. Probabilities are likely to be inestimable or very tentative at best.[11]

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[10] We believe this term was originally suggested to describe such uncertainty in natural resource problems in some of the unpublished work of Alan Randall. He used the term in Randall (forthcoming). Randall and Thomas (1991, p. 15) explicitly suggested that "the problem is one of ignorance rather than mere risk and uncertainty," thus anticipating the argument made here.

[11] For example, how does one deal with the logical requirement that probabilities summed across all outcomes must equal unity if some of the possible outcomes are not known?

As is clear from any recent issue of mainstream economic journals, the standard procedure for dealing with uncertainty involves assuming that outcomes and associated payoffs are known and probabilities are known at least in subjective terms. It is worth asking whether such approaches are applicable to ignorance. Perhaps strategies are needed that address ignorance directly, rather than trying to fit the problem into a risk framework.[12] At any rate, as we move from theory to policy, ignorance must be explicitly considered.

From Macro-Level Theory to Micro-Level Decision Criteria

Sustainability, as defined in this paper, is a macroeconomic concept. Either an economy, taken as a whole, is on a sustainable path or it is not. To ask whether a specific macroeconomic alternative is "sustainable" or not makes sense only in the context of the economy as a whole. A discussion of macroeconomic issues associated with sustainability and national income accounting are discussed in Appendix A. In the meantime, some attention needs to be devoted to considering how to go from the macroeconomic status of the economy **vis-à-vis** a sustainability constraint to criteria that can be applied to macroeconomic-level decision making.

In a sense, our goal is to develop microeconomic criteria for specific resource decisions. We take it for granted that actual decisions relating to sustainability will have to occur in a piecemeal fashion. In both the public and the private sectors, management of natural resources involves many individual choices over time. Our task is to explore whether criteria can be developed to judge whether each such decision is, in some sense, "sustainable."

As we are using the term macroeconomic, Pareto efficiency is also a macroeconomic concept. An economy as a whole is either on its Pareto frontier or it is not. It is instructive to consider how the transition from the macroeconomic level to the microeconomic level works for efficiency. That actual economic decision making about the allocation of specific resources must be piecemeal is taken for

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[12] Perrings (1991) suggests the use of a notion of uncertainty based on Shackle (1952) as an alternative to standard risk analysis in such situations.

granted. An economist who notes that a Pareto condition is violated in some specific instance, prescribes policies to make the economy “more efficient” with respect to that specific micro-level problem. Doing so raises second-best considerations. Given that inefficiencies are present in many sectors of the economy, applying the Pareto conditions piecemeal is unlikely to be fully optimal and the result of an intervention intended to improve economic efficiency could actually reduce aggregate social welfare. However, attempting to fine tune micro-level decision criteria to account for inefficiencies elsewhere is normally not practical. In practice, the economist hopes that application of simplified efficiency criteria in arriving at individual public decisions will improve efficiency most of the time.

Similar strategies will be required if sustainability is to be translated into workable criteria at the micro-level. A decision alternative maybe said to “enhance sustainability” or “make the economy more sustainable” if it expands the aggregate economic opportunities available to future generations. In a partial sense, it maybe relatively easy to determine how the policy is affecting a few components of the endowment. Much more difficult to anticipate, however, are the indirect effects of physical spillovers and reactions by economic agents to the new policy. As we have pointed out already, economic opportunities depend on the full endowment vector including non-resource components as well as natural resource components. If the policy indirectly leads to changes in the economy that affect other components of the endowment by diminishing their quantity or quality or inhibiting their growth, then, in net, the policy might have a negative effect on sustainability.

Such complications are analogous to the problem of the second best of efficiency analysis. For example, consider a policy that would encourage soil conservation and would not, in any identifiable way, impede social progress. Society might proceed with this intervention in order to enhance sustainability, only to learn that it led farmers to use more chemicals that contaminated groundwater. Just as sectors of the economy are interlined by market signals that affect whether a given projector policy is efficient, so resource and non-resource endowments are linked both in nature and through the economy in complex ways. Obviously such linkages should be identified and evaluated to the extent possible in considering whether public or private decisions will enhance sustainability. But, the ability to trace such effects is likely to be limited in practice. Following the efficiency analogy, the analyst can do little more than hope that the more obvious effects of choosing alternative courses of action will be sufficient most of the time to indicate whether those alternatives will enhance or reduce future economic opportunities.

Trade-offs between different components of the vector of endowments must be carefully considered in judging the sustainability-enhancing potential of a particular choice. Our example of soil versus groundwater illustrates this well. Suppose that, without a project, future generations living in a certain region will inherit less soil but purer groundwater. If the soil conservation project is adopted, the opposite will be true. Which alternative would contribute most to their utility possibilities is not obvious at first glance. If soil erosion is economically irreversible over relevant time spans, but groundwater could be purified using known technologies at modest cost, the soil erosion control project might be judged as contributing positively to sustainability. There are likely to be many judgment calls on such issues.

Confronted with ignorance and the possibility of unexpected consequences of interventions designed to enhance sustainability some will no doubt decide that the whole problem of sustainability is intractable and choose to ignore it. The theory of the second best and concerns about economic fairness have led some to adopt a similar attitude with respect to economic efficiency. Others, whether the issue is efficiency or sustainability, accept second best problems and ignorance as facts of life, and try to figure out how humankind might muddle through anyway. As part of the latter group, we will now proceed to consider policies that might help to achieve sustainability goals.

PRACTICAL STEPS TOWARD AN EFFICIENT, SUSTAINABLE ECONOMY

Two preliminary steps toward practical implementation of the framework developed here will be discussed. First, we shall consider the Safe Minimum Standard of Conservation for endangered species, reinterpreting this long discussed concept as a sustainability constraint. Second we turn to global warming, focusing on how a carbon tax would work in an economy seeking an efficient, sustainable path. In both of these examples, we emphasize that if sustainability is to be achieved, policies should explicitly consider this goal. Efficiency based analysis alone will not ensure sustainability.

The Safe Minimum Standard

Extinction of plants and animals is an economic issue because it narrows the biological diversity upon which current and future generations may depend for the stability and productivity of the ecosystems within which human activities must be conducted. Furthermore, the earth's plants and animals provide a reservoir of potential new resources to produce food, building materials, aesthetic enjoyment, energy, paper products, pharmaceuticals, transportation, recreation, and other desired commodities and services. Maintaining a sufficiently diverse flora and fauna has the potential to contribute to both economic efficiency and sustainability.

As long as human-caused extinctions were rare, there was little need for concern. Species diversity was a free gift of nature. At the end of the Twentieth Century, however, species diversity can no longer be taken for granted. Thousands of species of plants and animals will be lost in the next few decades unless steps are taken to save them. Such steps, however, would require the commitment of scarce capital, labor, and natural resources. Thus, on the one hand, massive extinction of living organisms may limit future economic possibilities. On the other hand, reducing the rate at which biological diversity is eroding will involve economic costs to the current generation that not only will harm its members but could conceivably affect the non-environmental endowments of future generations. In the terms developed here, extinctions threaten efficiency and sustainability, but measures to protect diversity could also have the potential to threaten both goals. Defining a sustainable, efficient course is not a simple problem.

The safe minimum standard of conservation (here abbreviated SMS) as originally proposed by Ciriacy-Wantrup (1952) and further developed by Ciriacy-Wantrup and Phillips (1970), Bishop (1978, 1980) and Randall (1991, 1995). Adopting the SMS strategy as a policy objective would mean avoiding extinction in day-to-day resource management decisions, Exceptions would occur only where it is explicitly decided that the costs of avoiding extinction are intolerably large or other social objectives must take precedence.

Randall (1991, p. 16) has explained the idea this way

> The SMS rule places biodiversity beyond the reach of routine trade-offs, whereto give up ninety cents worth of biodiversity to gain a dollars worth of ground beef is to make a net gain. It also avoids claiming trump status for biodiversity, permitting some sacrifice of biodiversity in the face

> of intolerable costs. But it takes intolerable cost to justify relaxation of the SMS. The idea of intolerable costs invokes an extraordinary decision process that takes biodiversity seriously by trying to distinguish costs that are intolerable from those that are merely substantial.

The SMS strategy does not involve a new economic paradigm but is instead a crude step toward the ideal of a fully efficient, sustainable economy. Because of ignorance about the future and other issues (Bishop and Woodward 1994), such an ideal is far from attainable. The SMS should be thought of as a practical strategy to be implemented in lieu of the ideal. The goal of the SMS strategy is to safeguard the economic opportunities of future generations by preserving some species that will prove useful and valuable to them and that would otherwise have been lost. The first-best solution to the problem, were it attainable, would involve an optimal endowment composed of a wide range of species and other resource and non-resource components. The SMS strategy is intended to push economies in that direction by augmenting future endowments of species diversity. Under the SMS, we presume that substitution of other components of the endowment for the species is difficult but not impossible. Costs of protecting a species become “intolerable” when it is believed that protecting a species might be so restrictive that both efficiency and sustainability would be inhibited.

The SMS strategy also requires consideration, within the limitations imposed by ignorance, of the implications of preservation for efficiency and for the non-environmental endowments of future generations. The social costs of choosing the SMS are important indicators of potential losses in efficiency and sustainability. Ignorance means that the full benefits of preserving specific species cannot be known. The higher are costs, however, the more likely they are to exceed benefits, were the latter filly known. Furthermore, though obviously any generalization would be questionable, one might expect that the higher are costs, the more disruptive will preservation of species be to social progress and hence to the non-environmental endowments of future generations. The SMS seeks to increase the future endowments of biological diversity without large sacrifices in efficiency or social progress.

Social costs here include the out-of-pocket costs for protecting species of plants and animals. For example, guards may be needed to protect an animal species from poaching. Opportunity costs, reflecting foregone resource uses, would need to be added in. Such opportunity costs might include, for example, the timber value of old-growth forests that must remain unharvested to provide habitat. External costs, such as livestock losses to an endangered predator, may also occur and need to be counted. Against these costs must be counted any measurable benefits from preservation. Some species, though endangered, may provide aesthetic enjoyment. Some members of society may hold existence values for preservation of endangered species of wildlife (Boyle and Bishop 1987; Bowker and Stoll 1988). If so, these should be counted. Because the long-term benefits that biodiversity may contribute through ecosystem stability and discovery of new resources are so difficult to anticipate, probably no allowance for them will be possible in most cases. We stress this problem by defining the net social costs of the SMS as out-of-pocket costs, plus opportunity costs, plus external costs minus measurable benefits. Measurable benefits are those benefits that can be expressed in monetary terms with reasonable confidence.

Whether the net social costs of the SMS are within the bounds of acceptability or not is a social decision that may have to be left to Randall's "extraordinary decision process." What we are asking, in part, is whether or not it is reasonable for the current generation to be required to make a given level of sacrifice to enhance the species diversity endowments of future generations. Such decisions involve value judgments beyond those that most economists are comfortable making. Societies, through the institutions of government, may have to consider such issues without direct help from economists.

Since the SMS depends upon the current generation's judgment as to what represents "intolerable" costs, it is nearly inevitable that either too many or too few species will be preserved under the SMS compared to the ideal. Because of ignorance about which species will ultimately prove valuable and which will not, to some extent, the wrong species will be saved. Some species that would have turned out to be of great value to future generations may be lost. Some species that will never be worth anything either directly or in terms of their contributions as parts of larger ecosystems maybe saved.

Note also that the SMS would only be one of many objectives of policy. As Randall stated in the quotation presented earlier, the SMS would not have "trump status." Many worthwhile objectives must vie for economic attention and public resources, and preservation of biodiversity probably would not take precedence in all cases. Most societies have a policy objective of preventing murder, yet the resources devoted to this end are not sufficient to prevent all murders. Similarly, if the SMS were an objective of policy, this would not mean that all extinctions of plants and animals would be prevented. The SMS policy would help limit extinction of plants and animals to those that can be saved only by bearing unacceptably high costs or through unacceptable sacrifices in other social objectives.

Randall (1991, 1995) has recently introduced a new and highly original framework for considering the SMS in the context of public policy formulation. This framework is useful in considering the relationships between efficiency and what we here term sustainability. Since loss of biodiversity raises intergenerational ethical questions, Randall reasoned that insights might be gained by considering it in the context of three major theories of ethics. Randall argued that making social choices based on benefit-cost analysis can draw some support from all of these schools but none would endorse benefit-cost analysis in an unqualified way. However, quoting Randall (1995, p.36),". . . it seems that the same general kind of decision rule - maximize net benefits subject to an SMS constraint --is admissible under the consequentialist, duty-based, and contractarian reasoning.” Since concerns about sustainability are grounded in ethics, this would appear to be a promising direction for additional work.

Global Warming and the Carbon Tax

The possibility of global warming due to the accumulation of greenhouse gasses in the atmosphere poses a very real threat to global sustainability. Based on climatic models and some empirical evidence, scientists believe that emissions of carbon dioxide and other “greenhouse gases” into the atmosphere is setting in motion a gradual warming of the planet. Though highly speculative, global climatic models predict that by the end of this decade greenhouse gases that will have accumulated in the atmosphere will commit future generations to a planet as much as three degrees Celsius warmer than the climate we enjoy today (Cline, 1992, Table 2. 1). Over the long run, even greater changes in the globe's climate are predicted. With this increase in temperatures will come a wide range of effects on humankind. Some effects will be positive, such as regional increases in agricultural production. Other changes will negatively affect society, such as the destruction of coastal ecosystems and real-estate due to rising sea levels. In net, it is generally believed that the effects of global warming will impose costs upon future generations (see, for example, National Academy of Sciences, 1992).

Emissions of greenhouse gases are intimately linked with the economy. Virtually all productive activities in developed nations use carbon based energy, contributing to the greenhouse warming. To some extent, our economic activities today are carried out at the expense of the climate of the next century. Using the language of this paper, our production today diminishes the climatic endowment of future generations. The greenhouse problem therefore, is fundamentally one of sustainability.

Despite the very long term distributional consequences of global warming, the debate within economics about how to best address the problem has centered on issues of efficiency. Nordhaus (1993), for example, refers to the greenhouse effect as “the granddaddy of public goods problems” (p. 18). When seen in this light, the problem can be reduced to a standard externality problem in which the level of greenhouse gas production is inefficiently high. Analysis motivated entirely by an efficiency perspective, however, will fail to address what we see as primarily one of sustainability since, as we have shown above, pursuit of the efficiency will not necessarily lead to sustainability.

The policy option to address global warming concerns that is most frequently discussed is a tax on carbon emitted by the burning of fossil fuels. This tax would encourage a reduction in the level of CO_2 emitted but would impose costs on some sectors of the economy. The costs of a carbon tax policy would take the form of a reduction in the quantity of goods and services that are produced using carbon based fuel. These costs would be borne by both current and future generations. The benefits of a carbon tax, on the other hand, would accrue primarily to the generations of the next century and beyond. As a result of reductions in greenhouse gas emissions, the planet would warm less than it would have without the policy, reducing the costs that will be borne by those generations. The efficient level for the tax is where the marginal benefit of increasing the tax equals its marginal cost. At lower tax rates, the marginal present value of benefits exceeds costs, at higher rates the marginal cost exceeds the benefits.

Implicitly, such efficiency measures look for the point where the timers from an additional reduction in gases can no longer payoff the losers. Elsewhere (Woodward and Bishop, forthcoming) we have argued that standard efficiency analysis of global warming implies a distribution of rights in which “the current generation has the right to emit endlessly and future generations are obligated to accept the consequences unless ‘they’ are capable of compensating ‘us’." While efficiency driven policies may diminish the warming experienced by future generations, under such a policy greenhouse gases would continue to accumulate and the planet will continue to warm. Efficient policies, therefore, will not eliminate the threat that the greenhouse effect poses to global sustainability.

As Beckerman argues above, it could be presumed that sustainability is not at risk because other components of the endowment vector are growing fast enough to more than compensate future generations for losses in the climatic endowment. In this case only the efficient level of reduction could be justified. The uncertainty in global warming analysis, however, is extreme. Of a surveyed group of experts, ten percent estimated that the damages associated with a three degree C warming would be 5.5 percent of world output or more while another ten percent had a median estimate of zero total loss or less (Nordhaus, 1993, p. 17). With such uncertainty on only one issue, how can we be certain that the multitude of changes in the endowment vector overtime will in net mean that the sustainability constraint is not binding? Sustainability may indeed be threatened, and if this is true, steps beyond those that can be justified on efficiency grounds maybe necessary.

In Woodward and Bishop (forthcoming) we propose that given these uncertainties, a prudent policy would be to address both efficiency and sustainability. Recognizing that global warming does have efficiency implications, a carbon tax should be used to reduce emissions at least to the point where the marginal benefits of a reduction in emissions equals the marginal cost. However, we argue that the carbon tax offers an opportunity to take “a full step in the direction of sustainability.” Since a carbon tax would generate enormous revenues, we suggest that those revenues should be used to explicitly compensate future generations by augmenting other components of the endowment vector. This could be done by improving environmental components of the endowment, stimulating technological progress, expanding infrastructure, even diminishing the debt burden that we pass on to our children (Bromley, 1989). Moreover, when global warming is seen as threatening sustainability, it might be acceptable to adopt a policy which reduces emissions beyond the level which follows from efficiency analysis in order to augment the climatic endowment of future generations. Just as intratemporal distributions cannot be justified on efficiency grounds, there is no reason to believe that a policy that redistributes intergenerational endowments would have benefits in excess of the costs.

The issue of global warming demonstrates well the importance of explicitly recognizing sustainability as a goal within economic analysis. The concern about the greenhouse effect arises not because we see the problem as reducing our total economic productivity, but because a sense of fairness and moral responsibility makes the status quo unacceptable to many. As such, while efficiency is important in discussing any policy alternative, it cannot be the sole criterion on which economists base their policy recommendations.

Conclusion

We have demonstrated in this paper that, if sustainability is deemed to be a social objective, then it both can and should be incorporated directly into economic analysis. Economic efficiency does not necessarily lead to sustainability. To ensure sustainability society must be take care to avoid violating its sustainability constraints. In theory, sustainability constraints can be determined which establish exactly the endowments that need to be passed onto the next generation in order to provide them with opportunities equal to those enjoyed by the present generation. In practice, exact determination of the sustainability constraint is impossible given the enormous uncertainty that dominates long-term economic and environmental issues. However, despite our ignorance and the complexity of interactions between the economy and the environment some guidelines for policy can be established.

The SMS and the carbon tax with associated spending priorities illustrate how sustainability constraints tight be implemented in practice. Obviously, a fully general constraint would have to cover a wide range of other resource issues, possibly including contamination of groundwater, soil erosion, deforestation, ozone depletion, and the like. In each such case, the endowments of future generations would need to be carefully considered in making resource management policy. Furthermore, a distinct approach would need to be developed to protect each such resource to give due attention to efficiency as well as sustainability. Once a more or less general constraint is in place, then it should be possible for both public and private economic agents to re-optimize to pursue the efficiency goal within the new regime of intergenerational endowments. In this way, the economy would move toward an efficient and sustainable path.

Appendix A: Sustainability Constraints and Indicators of Sustainability

While in practice it may be impossible to find the sustainability constraint with precision, the construct can be used to understand the meaning of sustainability. Consider a capital-resource economy in which sustainability is possible so that the sustainability constraint converges to a single locus. An implicit function $O^*(K_g,S_g)=\underline{O}$, can be defined where $\underline{O}$ is a constant and $O^*(\cdot)$ closely approximates $\overline{O}_g(C^*)$. Taking the total differential of $O^*(\cdot)$, we find that along the sustainability constraint

$$\frac{\partial O^*}{\partial K}\cdot\Delta K+\frac{\partial O^*}{\partial S}\cdot\Delta S\approx 0.$$

Hence, an approximate rule for sustainability would be to ensure that

$$\frac{\partial O^*}{\partial K}\cdot\Delta K+\frac{\partial O^*}{\partial S}\cdot\Delta S\geq 0$$

This constraint is similar to many other linear rules for sustainability, such as Hartwick's (1977) rule that the scarcity rents from a resource should be reinvested to ensure sustainable growth. This relationship is also similar to the implicit rule that in natural resource accounting studies which estimate the depreciation of natural resources. What distinguishes the rule derived from the sustainability constraint is that it is grounded only in the production possibilities of the economy and does not assume that the economy is operating on the efficiency frontier.

Consider a simple estimate of the net domestic investment (NDI) as might arise from a natural resource accounting study. Accounting for both the appreciation and depreciation of the capital and resource sectors, net investment is estimated, $NDI=p_K\cdot\Delta K+p_S\cdot\Delta S$. If the estimated value of NDI were greater than zero, this might be interpreted as indicating that the economy is on a sustainable path since the value of the total endowment has not diminished. This rule will be consistent with sustainability, however, only if $\frac{\partial O^*}{\partial K}\Big/\frac{\partial O^*}{\partial S}=p_K/p_S$. Since prices in an economy are critically dependent upon the distribution of endowments across agents in the economy (see Howarth and Norgaard, 1990), it is not guaranteed that the market prices would be appropriate even in a perfectly functioning market economy. The problem becomes more severe if the endowment has public good characteristics (e.g., national parks), markets do not exist for portions of the endowment (e.g., the climate) or other sources of market failure are present. The sustainability constraint, therefore, provides a useful target for valuation in natural resource accounting studies.

This framework, therefore, provides a new perspective on economic indicators of sustainability. By working directly with the sustainability constraint we allow for substitution, but do not presume that markets provide all necessary information with perfection. Of course the framework is not fully developed and, would certainly have substantial informational needs, perhaps even more so than standard environmental accounts (United Nations, 1993). We would argue that the returns might be higher since such an approach leads directly to the societal sustainability constraint and, therefore, is a better indicator of the economy's sustainability.

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ACCOUNTING FOR THE ENVIRONMENT
IN AGRICULTURE

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and

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Abstract

Detailed information derived from the national income and product accounts provide the basis for economic interpretations of changes in the nation's income and wealth. Our intent in this paper is to more accurately measure agriculture's contribution to national income. We develop a theoretically consistent framework for incorporating natural capital and environmental goods into the existing income accounts. Next, we apply the framework and adjust agricultural income and national income to reflect the depletion of natural capital (land and water) caused by agricultural production and the non-market effects of agricultural production on output in other sectors of the economy and consumers. Specifically, the effects of soil erosion on agricultural productivity and income, the economic effects of decreased water quality, and the depletion of water stocks are presented as examples of the potential scope of accounting adjustments needed in the agricultural sector. Estimated adjustments to net agricultural income are in the range of $4 billion and have declined as a percentage of net farm income since 1982. Our estimates suggest that agriculture's contribution to social welfare far exceeds the environmental damages and deterioration of the stock of natural capital resulting from the production of food.

National income accounting is one of the most important economic policy making tools developed in the last 50 years. Detailed information derived from the accounts provide the basis for economic interpretations of changes in the nation's income and wealth. These national income and product accounts (NIPA) through their measures on Gross Domestic Product (GDP) and Net National Product (NNP) often provide the only meaningful indicator of the effects of public policy interventions, Nearly from the inception of national income accounting, however, economists have criticized the NIPA by identifying inconsistencies with the underlying theory and the empirical application of the theory.

Early criticism of the NIPA centered around the treatment of capital, leisure, and government expenditures. Recent critiques, with historical roots in the early 1970s, question the use of estimates of NNP as a measure of social welfare because it does not account for the value of changes in the stock of natural resources nor does it include the value of environmental goods and services. Critics question the credibility of the accounts because natural and reproducible capital are treated asymmetrically and the value of non-marketed environmental goods and services is not captured (Prince and Gordon, 1994).[1] NNP, it is argued, is not a useful measure of long-term sustainable growth partly because natural resource depletion and environmental goods are not considered. The failure to explicitly consider the environment in the accounts misrepresents the current estimate of well-being, distorts the representation of the economy's production and substitution possibilities, and fails to inform policy-makers on important issues related to economic growth and the environment.

Several attempts to adjust income measures to account for the environment exist. it is most common for these studies to focus on accounting for natural resource depletion (Repetto, 1992; Smith, 1992; Nestor and Pasurka, 1993; U.S. Department of Commerce, 1994).[2]

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[1] Our definition of non-marketed goods includes environmental amenities and disamenities.

[2] Smith (1992) suggests his work should be characterized as environmental costing rather than environmental accounting.

Theoretical and empirical problems persist, however, particularly when the level of environmental services and damages are estimated. For example, no consistent approach for the treatment of “defensive expenditures” in response to or in anticipation of environmental injury has emerged from the literature (Ahmad, El Serafy, and Lutz, 1989).

Our intent in this paper is to more accurately measure economic well-being. Improving the measure of current economic activity requires incorporating non-market final goods and bads into the existing accounts. Economic well-being, however, extends beyond current economic activity and must also reflect future production possibilities. We begin by developing a theoretically consistent framework for incorporating natural capital and environmental goods into the existing income accounts, Next, we empirically apply the framework and adjust agricultural income and national income to reflect the depletion of agricultural natural capital (land and water) and the non-market effects of agricultural production on output in other sectors and consumer utility.

The theoretical framework developed for this study is grounded on the work of Arrow and Kurz (1970), Weitzman (1976), Solow (1986), Hartwick (1990), and Mäler (1991). Weitzman has shown that the current-value Hamiltonian in a neoclassical growth model of the aggregate economy can be interpreted as NNP.[3] Solow incorporated exhaustible resources as distinct capital assets into Weitzman’s treatment of NNP. Hartwick and Maler extended Solow’s approach to capture renewable resources and environmental capital (pollution abatement). In our analysis, the Hartwick-Solow-Weitzman framework is extended to include three production sectors (agriculture, non-agriculture, and household production). This extension allows us to adjust both agricultural and national income. Rather than viewing non-market environmental goods as externalities, we follow the prescription of Solow (1992) and cast the environment as a set of natural capital assets providing flows of goods and services to the economy. Economic use of natural capital results in feedback effects: depletion of stock of natural capital reduce future flows of goods and services from the environment, degradation due to the disposal of residuals results in costs imposed on third

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[3] This interpretation requires a re-normalization of the current value Hamiltonian.

parties. In addition, firms and households are allowed to make expenditures for pollution abatement and control.

Results from a dynamic optimization model are utilized to adjust NNP and net farm product (NFP) for the use of natural capital assets. in addition, NNP reflects the value of net changes in capital goods (net investment) and the value of net changes in the stock of natural capital. Optimizing the current value Hamiltonian yields scarcity values for all capital stocks including natural capital. The optimization process, therefore, generates relationships for adjusting current NNP to account for the current value of the loss of natural capital stocks from using exhaustible resources and depleting and degrading renewable and environmental resources.

Theoretical results from our model mirror Hartwick's results. That is, GDP includes priced resource input flows and these flows from capital stocks should be off-set by deductions from GDP to incorporate the value of changes in natural resource capital stocks to arrive at NNP.[4] Our empirical application suggests only minor changes are necessary when agricultural natural resource effects are incorporated into the national income accounts. Adjustments to the national accounts are minor because agricultural production is a small component of GDP (less than 2 percent) and most extra-agricultural effects are currently captured in GDP. Larger changes are warranted, however, in the adjustment of net agricultural income, Most effects represent income transfers between agriculture and other sectors.

Agricultural income is adjusted to reflect the value of changes in the stocks of "effective" farmland, water quality, and the stock of ground-water. These natural capital stocks may change due to damages associated with agricultural production. Specifically, the effects of soil erosion on agricultural productivity and income, the economic effects of decreased surface-water quality, and the depletion of ground-water stocks are presented as examples of the potential scope of accounting adjustments needed in the agricultural sector. We adjust income for changes in the stock of ground-water because in some regions there has been a sustained withdrawal of ground-

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[4] Possible increases in the value of natural or environmental capital are not excluded.

water stocks in some regions of the United States. Our estimated adjustments would require net agricultural income to be revised downward by $4 billion (6 percent). These estimates of adjustments to net farm income are consistent with a view of U.S. agriculture where environmental problems exist and the resource base is depreciating, but also suggest that agriculture's contribution to social welfare far exceeds the environmental damages and deterioration of the stock of natural capital resulting from the production of food.

National Income Accounting

The national income and product accounts (NIPA) were developed primarily to monitor the macroeconomic performance of the economy. The most widely used measure or statistic of economic activity is gross domestic product (GDP). GDP is highly correlated with employment and capacity utilization and therefore central to how business cycles are defined and tracked.

A simple circular flow diagram is a powerful model to illustrate the flow of final goods and services from the business sector to the household sector and the" concurrent flow of factor services from households to firms (Figure 1). In a monetized economy, goods and services exchange for consumer expenditures while primary factors of production (endowments of capital,

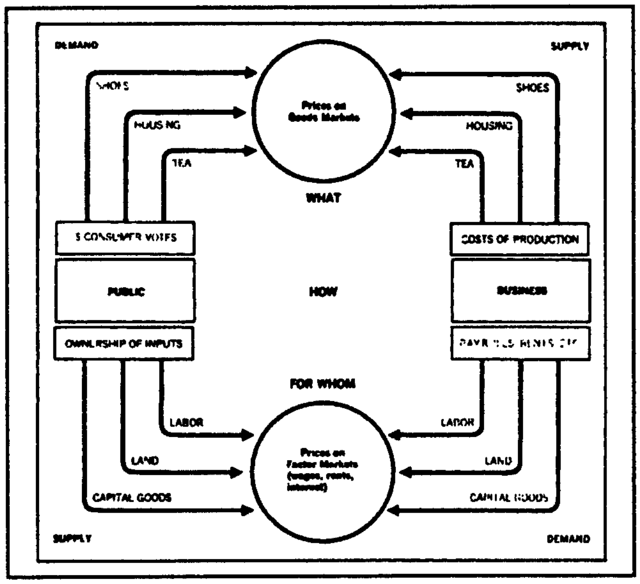

Figure 1. Circular Flow Model

labor, and land) exchange for wages and salaries, rent, interest, and profit. The circular flow model suggests two methods for measuring the monetary value of current GDP: flow-of-output and flow-of-income. In a flow-of-output approach, all expenditures on final goods and services are added together. This measure captures the transactions from the "upper loop" of the circular flow model and includes the value of new capital (gross investment), government purchases of goods and services, and net exports. The flow-of-income alternative yields an equivalent measure of GDP and is computed by summing payments to the primary factors of production. Because GDP is a measure of final goods and services, purchases of intermediate goods must be excluded. The failure to exclude intermediate goods and services from national income results in "double-counting" and an over-statement of the level of economic activity.

Table 1 provides a summary of the NIPA for 1992. The table illustrates the flow-of-income and flow-of-output approaches. Though arrived at in different ways, the calculation of national income and GDP are equal in either case ($6 trillion). The flow of income approach include compensation of employees ($3.6 trillion), proprietors income ($0.4 trillion), corporate profits ($0.4 trillion), net interest ($0.4 trillion), and rental income. The flow of output approach includes expenditures on final goods and services by households ($4.1 trillion), the government ($1.1 trillion), and gross investment by firms ($0.8 trillion).[6]

Net of taxes, the largest single item differentiating GDP from national income is the consumption of fixed capital or depreciation. For 1992, U.S. GDP exceeded $6 trillion while national income approached $5 trillion. Depreciation of the U.S. capital stock was estimated at $657.9 billion or about 11 percent of GDP. The concept of capital stock depreciation is particularly important when we turn our attention to natural capital and environmental assets.

Table 2 summarizes the calculation of farm income for 1992 using a flow-of-income approach. Gross farm income in 1992 was $84.4 billion or about 1.4 percent of U.S. GDP. While

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[6] However, the current NIPA system attributes household and government investment to current consumption.

wage income (compensation to employees) is by far the largest income category at the national level (74 percent of U.S. national income), proprietors income (65 percent) and net interest (15 percent) are the largest components of net farm income. Consumption of fixed capital in agriculture is 26 percent of gross farm income, over twice as large as the aggregate national rate.

Income accounts are subject to mismeasurement either by improperly including or excluding items. Including the exchange of intermediate goods and services in the measure of national income is an example of improper inclusion. Similarly, counting transfer payments or non-productive redistributions such as social security payments, welfare payments, and agricultural deficiency payments as gross income is inconsistent with the received definition of national income.

Improper exclusion occurs when the value of a final good or service is not included in the accounts. This occurs when a good or service is traded in informal markets commonly referred to as the "underground economy." Often these transactions in the form of "cash-only" arrangements are undertaken to avoid taxes. "Non-market" goods and services are also often excluded from the income accounts because they are difficult to measure. Examples include unpaid housework and child-care and environmental goods and services. In some cases, market values have been imputed for "non-market" goods and the income accounts adjusted accordingly. The value of housing services received from owner-occupied houses is the best example.

The treatment of several elements in the accounts remain controversial and unclear, Leisure, for example, has properties associated with a normal economic good. Yet, whether and how to include the consumption of leisure in the national income accounts is unresolved. Another example is criminal activity. Criminal activity is typically viewed as reducing not enhancing social welfare and therefore not included in GDP. Legal gambling services in Nevada and New Jersey are, however, included. Excluding criminal transactions reflects a moral judgement about the desirability of illegal goods and services as indicators of social well-being. The cost of this moral judgement is to reduce the accounts usefulness as a measure of economic activity.

Government expenditures on military defense, police, and environmental clean-up add to the conventionally measured income accounts. Nordhaus and Tobin (1972) argue, however, increases in these expenditures reflect the increasing "disamenities of urban life" that decrease social well-being. Similarly, increases in household "defensive" expenditures on items like mace and bottled water may signal a decrease in social welfare.

Environmental Accounting

Environmental accounting addresses the improper exclusion of the services provided by environmental goods and the asymmetric treatment of natural capital and reproducible capital within the existing accounts. Including the provision of environmental goods and services greatly increases the complexity of properly adjusting the income accounts. Environmental goods and services rarely have observed market prices or easily measurable market quantities. The absence or incompleteness of these markets can have distorting effects on the good for which markets exist. Thus, even if environmental goods and services are not included in the accounts, their existence may cause distortions in the relative prices in traditionally measured sectors. If so, the view of measured NNP as the current consumption value of a dynamically optimal resource allocation is flawed.

Income accounting in the U.S. does not correct for price distortions. In developing countries, however, significant effort is made to correct income accounts for market distortions when the correction may be important for deciding among competing investment projects. The implicit rationale for not adjusting market prices in developed countries is markets are well developed and distortions, to the extent they exist, are small. However, price distortions with respect to environmental and agricultural goods may be relatively large.

Changes in environmental quality have multiple effects across sectors and consumers. Producers are affected because changes in environmental quality can affect the productivity of other resources. Consumer utility is affected directly through changes in consumption and indirectly through effects in option or existence value. Environmental effects are, therefore, a mixture of private good, public good, and quasi-public good effects.

The income accounts can be extended using the flow-of-output approach to value environmental goods and services produced. To avoid double-counting it is important to capture only the value of the final environmental goods and services, Accounting for intermediate external effects is needed only to compute sectoral income. If, however, an accurate measure of national income alone is sought, then intermediate external effects can be ignored. In many cases externalities are intermediate goods whose value is imbedded in the bundle of final goods and services. Including the intermediate good in the income accounts is double-counting. A similar argument holds for the flow-of-income approach. Economic rents generated by a non-market externality are captured in payments to factors of production.

Accounting for non-market goods requires adjusting GDP for environmental goods and services and transactions from the informal or underground economy. If changes to income consist largely of accounting for environmental effects, then adjusted aggregate income might be termed “green GDP”. Adjusting GDP requires deriving a shadow price and physical measure for each final non-market good. No information is necessary on intermediate goods.

There is considerable agreement that national accounts, although flawed, are useful measures of economic performance and these accounts can be modified or extended to improve the measure economic activity. Some economists have argued for developing alternative accounting systems. Satellite accounts, a related but separate set of environmental accounts, may be a preferred alternative to further diluting the quality of the market-based data with imputed transactions. Critics of integrating the accounts argue that although flawed, the current income accounts reasonably represent the market economy. Satellite environmental accounts would include current market environmental expenditures as well as shadow accounts for non-market environmental goods. A complete system of satellite environmental accounts would allow the analyst to calculate the non-market adjustments and trace productivity effects across sectors.

The United Nations System for Integrated Environmental and Economic Accounting (SEEA) is a set of satellite environmental accounts supplementing the current System of National Accounts (SNA).[6] The intent is to develop an environmental accounting framework consistent with the concepts and principles underlying conventional income. Harrison (1989) presents criteria for guaranteeing the satellite accounts are complementary to rather than a substitute for the current accounts. A primary requirement is the parallel treatment of "natural capital" (natural resources) and physical capital in the national accounts.

Although there have been other attempts to capture environmental effects in national accounts (Nordhaus and Tobin, 1972), Nestor and Pasurka (1993) is the most ambitious. Nestor and Pasurka disaggregate the U.S. input-output tables into environmental and non-environmental components, Adopting the framework of Schafer and Stahmer (1989), Nestor and Pasurka divide the environmental account into three categories. The "internal environmental protection sector" captures intermediate goods and services produced and used within the environmental protection industry. The "external environmental protection sector" captures the purchase of intermediate inputs from outside the sector. Examples include waste disposal, sewage treatment, and environmental construction activities. The "final demand sector" for environmental protection includes fixed capital formation for environmental protection, direct pollution abatement activities by governments and households and net exports of environmental protection goods.

The Nestor and Pasurka approach is consistent with the proposed system for environmental and economic accounts (United Nations, 1993) and indicates the importance of environmental protection activities in GDP. Through disaggregation, they estimate the 1982 total value-added for environmental protection to be 0.3 percent of GDP. This is less than 20 percent of the $80.6 billion (1.7 percent of real GDP) estimate of real pollution and abatement control expenditures for 1991 (Rutledge and Leonard, 1993). While the Nestor and Pasurka approach provides more information on the contribution of market expenditures on environmental protection, it does not

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[6] See United Nations (1992) and Bartelmus, Stahmer, and von Tongeren (1991).

change the overall measure of GDP because it does not include non-market activities.

NNP and Welfare

NNP is the premier indicator of current market-based economic activity. NNP has also been promoted and, more importantly, interpreted as an indicator of social welfare. Samuelson (1961) rejected all current income concepts as meaningful welfare measures and argued instead for a “wealth-like magnitude” such as the present discounted value of future consumption. Weitzman (1976) bridged the gap between Samuelson’s argument for a wealth-based indicator of welfare and current measures of income by demonstrating NNP captures both current consumption and the present value of future consumption. A current income concept and a wealth-like magnitude, he argues, “are merely different sides of the same coin." Weitzman’s results are illustrated in figure 2.

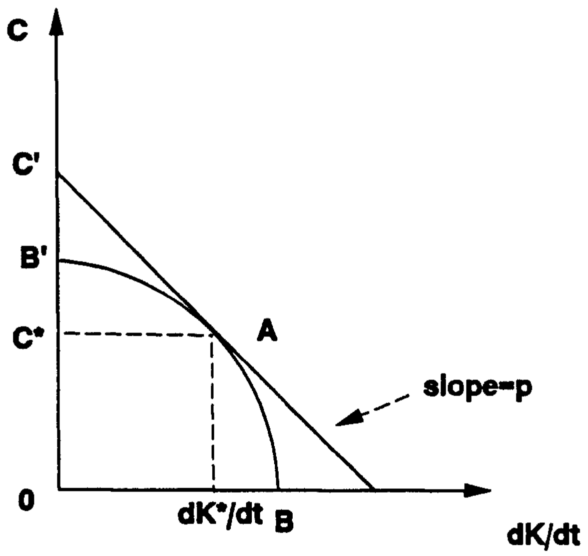

Figure 2. National Income

In figure 2, the production possibilities frontier B'B represents the economy's technical ability to transform investment goods into consumption goods. The budget constraint C'C represents society's willingness to trade-off future consumption for current consumption which depends on the rate at which society discounts future consumption. The economy is located at point A on the production possibilities frontier B'B. Optimal consumption and net investment are given by C* and dk*/dt. Real NNP, is geometrically represented as OC'. The only point where measured income is supported by production is at A. OC' is a strictly hypothetical consumption level at the present time, because the largest permanent consumption level obtainable is OB'. Production and income are equivalent only at A unless the transformation of investment goods into consumption goods does not exhibit diminishing marginal returns. That is, if the production possibilities frontier is linear, OB' is income, where income is interpreted as the maximum consumption possible. The correct measure of "income" or NNP at the dynamic optimum is indicated by A. The level of constant consumption OC' gives the same present value of welfare as the discounted maximum welfare received along the optimal consumption path. Thus, Weitzman calls OC' the stationary equivalent of future consumption.

Weitzman argues, income accounts, properly measured, provide a measure of the welfare of society and give concrete economic form to the concept of sustainability. The current income accounts do not adequately measure welfare or sustainable income because they fail to consider non-market environmental goods and services and the degradation or depletion of non-renewable resources.

If natural capital has a market, but is excluded from the accounts, then the accounts fail to accurately measure true NNP. The only correction needed is to adjust the national accounts is to deduct the value of the natural capital consumption (resource depletion). If natural capital does not have a market, however, or the market price is distorted, then adjusting the accounts for natural capital consumption is not as straightforward. Difficulties arise because there is a non-optimal level of resource depletion and the shadow-price of resource depletion, an endogenous value, differs from the socially optimal price. Similarly, if natural capital is substitutable for reproducible capital, properly measured NNP also represents the maximum level of sustainable income for society. However, if natural capital cannot substitute for reproducible capital, the link between aggregate NNP and sustainable income is more problematic.

Application Framework

In this analysis, the environment and natural resources are treated as natural capital assets generating a flow of services. Such a treatment allows for substitution between natural and reproducible capital and is consistent with notions of weak sustainability. By adjusting national income for changes in environmental quality and natural resource stocks, the national accounts provide a more accurate economic interpretation of changes in the nation's assets. This approach implies information about stocks on their own is not a sufficient statistic for well-being.

The model developed for this analysis draws significantly on Hartwick (1990) and Mäler (1991). Our work differs from previous work in that our model includes three production sectors (agriculture, non-agriculture, and household production), three roles for land, and equations describing the change in "effective" productivity of farmland, surface water quality, and the stock of ground-water over time. Land, surface-water quality, and the stock of ground-water are treated as natural capital.

Land in its natural state contributes directly to social welfare but is not used in any production sector. Land is used in the agricultural sector and also contributes directly to social welfare by providing rural landscape. We distinguish between the productivity of farmland and its role in providing rural landscape because efforts to increase productivity are not likely to provide added rural landscape. The third use of land is as an input in the production of non-agricultural goods. This land makes no direct contribution to social welfare, but influences welfare by contributing to the production of non-agricultural goods and services.

Water quality directly contributes to social welfare and is also an input into the production of non-agricultural goods. Agricultural production, however, adversely affects water quality as a result of soil erosion and chemical run-off. We adjust income for changes ground-water stocks because in some regions there has been sustained withdrawal ground-water over time.

Each of our natural capital assets are regenerative or renewable but may be exhausted from over-use if the rate of use exceeds the natural and managed regenerative rate of the asset. The net rate of regeneration is the rate at which the stock of the asset changes over time.[7] For land, surface-water quality, and the stock of ground-water, the net rate of regeneration depends on the intensity of use, the natural rate of regeneration, and the effectiveness of management to offset the intensity of use of the asset. Land, for example, is usable until the productivity of soil for producing agricultural goods approaches zero. The loss in soil productivity is offset by the soil's natural capability to regenerate itself. The productivity of soil to produce agricultural goods is also enhanced (managed) by applying labor, intermediate inputs (fertilizer), and capital to improve soil quality.

Surface-water quality is characterized in a similar fashion. Natural regenerative processes offset surface-water quality deterioration. The net rate of regeneration is a function of water quality damage from agricultural production, the natural rate of regeneration, and the effectiveness of management to offset degradation. The treatment of ground-water is potentially more problematic because there may be resource degradation associated with the water stock's quantity and quality. Treatment of ground-water in this analysis does not consider changes in ground-water quality.

While agriculture's share of NNP includes a deduction for the consumption of physical capital, a similar deduction is not made for other types of capital including farmland or natural resource stocks such as water quality or water quantity, In addition, NNP is not adjusted for externalities associated with agricultural production. For example, agriculture's contribution to NNP is not reduced by offsite damages to water quality associated with soil erosion.

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[7] The net rate of regeneration defines the equation of motion for each asset.

In this analysis, farm income is adjusted to reflect changes in the effective level of farmland in agriculture over time and the damages associated with soil erosion on surface-water quality. We also correct farm income for the sector's contribution to the overall decline in the stock of ground-water. Because data is limited, the value of scenic preservation of farmland and the value to society of land in its natural state are not addressed. We also do not correct for the value of leisure, We do not correct GDP or NNP for the value of leisure or the production of household output.

For the interested reader, the theoretical model is developed in detail Appendix A. The work of Weitzman and originally Arrow and Kurz (1970) provide the necessary connection between the current value Hamiltonian and NNP. In their work and our model, net welfare is expressed as the linearized version of the current value Hamiltonian, NNP is reduced to the sum of the social value of an economy's consumption and the social value of the changes in its capital stocks. By capital stocks we mean manufactured or reproducible capital as well as natural capital stocks.

Net welfare measure in terms of final goods and services is:

$$
\begin{aligned}
NWM \approx{} & \frac{\partial U}{\partial q}\left[\frac{\partial q}{\partial n_1}n_1 + \frac{\partial q}{\partial k_1}k_1 + \frac{\partial q}{\partial Z_1}Z_1 + \frac{\partial q}{\partial T_1}T_1 + \frac{\partial q}{\partial W_1}W_1\right] \\
& + \frac{\partial U}{\partial x_2}\left[\frac{\partial x}{\partial n_2}n_2 + \frac{\partial x}{\partial k_2}k_2 + \frac{\partial x}{\partial Y}Y + \frac{\partial x}{\partial L_2}L_2\right] \\
& - \frac{\partial U}{\partial x_2}\left[x_3 + x_4 + x_5 + x_6 + l_1 + l_2 + l_3 + l_4 + l_5 + l_6\right] \\
& + \frac{\partial U}{\partial Y}Y \\
& + \sum_{i=1}^{6} \mu_i \dot{k}_i + \rho_3 \dot{T}_1 + \rho_4 \dot{Y} + \rho_5 \dot{W}_1 \qquad (1)
\end{aligned}
$$

The first line of equation (1) represents expenditures on final goods and services produced by the agricultural sector as the sum of the value of the marginal contributions of each input used in producing the agricultural good. That is, the expenditures on final agricultural goods is the sum of the value of labor (n_1), capital (k_1), an environmental input (Z_1), effective farmland (T_1), and the stock of ground-water (W_1) that is used to produce the agricultural good. The inputs used to produce the agricultural good are valued in terms of the marginal contribution of the agricultural good to the utility of society $(\partial U/\partial q)$. The second line in equation (1) represents expenditures on total goods and services produced in the non-agricultural sector. Expenditure on these goods is a function of the value of labor (n_2), capital (k_2) water quality (Y), and land (L_2) used to produce non-agricultural goods, valued in terms of the marginal contribution of these goods to the utility of society $(\partial U/\partial x_2)$. The third line in equation (1) represents expenditures on intermediate inputs used to produce the agricultural and non-agricultural goods and services. Intermediate expenditures are excluded from NNP to avoid double counting.

Deleterious environmental effects from agricultural production increase the cost of production and require devoting additional productive resources to improve damaged water quality. These additional intermediate inputs in the production of non-agricultural output are reflected in lower current measured output in final consumer goods. The long-term effects on the production of final consumption goods caused by environmental damages from agricultural production are not included in conventionally measured NNP.

The fourth line in equation (1) represents the value $(\partial U/\partial Y)$ of the stock of clean water (Y) to consumers. This value is also not captured in conventionally measured NNP. The final line in equation (1) reflects the addition of the value of net investment in both reproducible capital $(\dot{k}_i)$ and natural capital: effective farmland (T), water quality (Y), and ground-water quantity (W). Current period production is valued in terms of its marginal contribution to the utility of society today. Net investment in both reproducible and natural capital are valued by their marginal contributions to the utility of society today and their marginal contribution to the utility of society in the future. [8]

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[8] The conditions for optimality are presented in Appendix B.

The last two lines in equation (1) represent our adjustment to NNP. We suggest that the conventional measure of NNP be corrected to reflect environmental impacts of agricultural production on the stock of clean water as well as the future environmental impacts of agricultural production on the stocks of effective farmland (T), water quality (Y), and ground-water quantity (W),

Effective Farmland/Soil Productivity

The link between agricultural production practices, erosion, and farmland's ability to produce output has been studied extensively (Crosson, 1986). In 1989, as part of the Second Resources Conservation Act (RCA) Appraisal, the USDA estimated a 3 percent loss in productivity over the next 100 years if farming/management practices remained as they were in 1982 (Table 3). Similarly, Alt, Osborn, and Colacicco (1989) found that the net present value of both the crop yield losses and the additional fertilizer and lime expenses associated with agricultural production totaled $28 billion, Both studies employ a crop production model, Erosion Productivity Impact Calculator (EPIC), which link production practices, erosion rates, and productivity, to provide estimates for physical depreciation rates of land.[9] Linking physical depreciation rates with crop prices can provide an estimate of economic losses attributable to soil erosion over time. However, a productivity loss of 3 percent over 100 years will not change NNP significantly.

While our theoretical model for adjusting NNP for the impact of erosion on loss of soil productivity is straightforward, it is more difficult to assess a more comprehensive view of land quality over time (National Academy of Sciences, 1993). For example, the RCA report also concluded that less than 50 percent of all agricultural land was "adequately" protected. Adequately protected soil was defined as soil within acceptable limits with respect to soil erosion and other factors limiting sustained use. Soil scientist have developed "soil loss tolerance" or "T-values" which vary by type of soil. A general rule of thumb is that erosion rates less than 5 tons

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[9] EPIC is a physical-process model that simulates interaction of the soil-climate-plant management processes in agricultural production. EPIC was developed by USDA/ARS scientists and has been used extensively in the RCA and elsewhere (e.g. Faeth, 1993).

per acre per year (T) do not result in damage to crop yields. Although results from the RCA seem to indicate soil erosions effect on productivity are economically unimportant, the report also indicates about 40 percent of cropland was eroding at rates greater than T.

Water Quality

More important than the productivity impacts of agricultural production on effective farmland are the impacts of erosion on water quality and therefore on recreation, commercial fishing, navigation, water storage, drinking supplies, industrial supplies, and irrigation. Ribaudo (1989) estimated the average annual offsite erosion costs for the U.S. at $1.78 per ton ($ 1986). Even if productivity effects are negligible, soil erosion associate with an acre of land causes, on average, $9 in offsite damages.

Because data is limited on wind erosion our estimates focus on the offsite effects associated with sheet and rill erosion, We link sheet and rill erosion and the adsorption of nutrients to soil particles to estimate the effects of agricultural production on siltation, stream sedimentation, and water pollution. Table 4 presents estimates of sheet and rill erosion for cropland and pastureland for 1982, 1987, and 1992 from the National Resources Inventory (USDA).

It is possible for agents to mitigate the effects of pollution through defensive expenditures of capital, labor, and other intermediate inputs. For example, increased siltation diminishes the usefulness of a reservoir for producing electricity. The effects of siltation can be offset by dredging. The attempt to offset the effects of soil erosion may result in additional costs (expenditures) in electricity generation. In this case, part of the costs of agricultural production are shifted to electricity generation. Similar arguments can be made for other industries. Economy-wide NNP, therefore, should not be increased or decreased to reflect the transfer of costs from one industry to another because aggregate NNP is correct. There is, however, a misallocation of income among sectors. Conventionally measured farm income is higher if the costs of repairing the reservoir are included as an intermediate expense of the affected industries rather than as an intermediate expense of agricultural production.

Soil erosion also affects consumer utility. An increase in sedimentation in a reservoir can reduce recreational activities. Because many recreational activities are unpriced and therefore are not included in conventionally measured NNP, the diminished value of the resource does not directly affect the income accounts although decreases in expenditures on complementary goods will appear. In the inter-industry example there was a misallocation of income but economy-wide NNP was accurate. In the second case, conventionally measured NNP fails to fully reflect the loss of welfare due to the loss of the recreational resource. Therefore, the off-site damages to consumers caused by agricultural production should be counted as an overall decline in NNP.

Similarly, the noncommercial loss of fish and waterfowl populations associated with increased sedimentation are not fully represented in NNP. In addition to the impacts on recreation, there may be an "existence" value component for the health of these riparian ecosystems. Such a value is also excluded from the national accounts as currently measured.

We do measure the stock of water quality (Y) or the marginal utility of water quality $(\partial U/\partial Y)$. Because no comprehensive measure exists, we use Ribaudo's (1989) estimate of the off-site damages to water quality from soil erosion. The off-site damages in dollars per ton of soil erosion (converted to $1982) are listed in table 5. The estimates reflect the off-site effects of soil erosion on freshwater and marine recreation, water storage, navigation, flooding, roadside ditches, irrigation ditches, freshwater and marine commercial fishing, municipal water treatment, municipal and industrial uses, and steam power cooling. We reorganize the damages into those affecting industry (water storage, navigation, flooding, roadside ditches, irrigation ditches, freshwater and marine commercial fishing, municipal water treatment, municipal and industrial uses, and steam power cooling) and those directly affecting consumers (freshwater and marine recreation). The industry and consumer damages per ton of soil erosion are highest in the Northeast.

The value of total damages presented in tables 6 and 7 are calculated by applying Ribaudo's per ton estimates to the total level of sheet and rill erosion for cropland and pasture by region.[10] Total damages are $4.4 billion 1992, with $3.0 billion associated with industry affects, Interestingly, while the dollar per ton effects are highest in the Northeast, the total industrial damages are greatest in the Southeast ($390 million).

The effects of sheet and rill erosion on consumers totaled $1.1 billion in 1982, $1.2 billion in 1987, and $1.3 billion in 1992. In addition to reducing farm income, these adjustments reflect a decline in NNP and overall welfare. The effects on other industries were about twice as large as the consumer impacts. Estimated industry effects are $2.4 billion in 1982, $2.7 billion in 1987, and $2.7 billion in 1992. While these adjustment lower agricultural income, they do not reflect a decline in NNP and overall welfare. They are treated as a transfer from one production sector of the economy to another.

Ground-Water Quantity

Our final adjustment to the national and agricultural sector accounts is an adjustment for the value of the change in the stock of ground-water over time. In the long-run, an equilibrium is generally reached in terms of recharges (precipitation, imports from other regions) and discharges (natural evapotranspiration, exports to other regions, consumptive use, and natural outflow) from any ground-water system. However, in five water resource regions, the rate of discharge has consistently been greater than the rate of recharge and has lead to a continued decline in the stock of ground-water (U.S. Department of the Interior). Those five regions are: the Missouri Basin (Montana, Wyoming, North Dakota, South Dakota, Nebraska, and parts of Colorado and Kansas), the Arkansas-White-Red (southern Kansas, Oklahoma, north Texas, and western Arkansas), the Texas-Gulf (most of Texas), the Lower Colorado (Arizona), and California. While it is difficult to assess agriculture's contribution to the overall change in the stock of ground-water in those regions, the sector accounted for 79 percent to 88 percent of total ground-water withdrawals in the U.S. (Table 8).

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[10] Ribaudo's 1982 estimates are inflated to 1987 and 1992 by the change in the gross domestic product implicit price deflator.

Because the most recent estimate of the change in the stock of ground-water for the U.S. is for 1980 (U.S. Department of the Interior) and because the data are not specified by sector of use, we adopt the following four step procedure. First, we employ the 1980 water resource budgets and use agriculture's share of total ground-water withdrawals (Solley, et.al.) to allocate the change in the stock of ground-water for each of the five water resource regions exhibiting declines in the stock of ground-water in 1980. For example, in 1980 agriculture accounted for about 86 percent of ground-water withdrawals in the California water resource region. Therefore, we assume that agriculture accounted for 86 percent (1.2 billion gallons per day (BGD)) of the total decline in the stock of ground-water in the California water resource region (1.4 BGD) for 1980.

Second, because water use data is collected every five years, we use the change in total ground-water withdrawals to update the total change in the stock of ground-water for each of the water resource regions. For example, from 1980 to 1985, the total (both agriculture and non-agricultural) withdrawals of ground-water for the California region fell by about 30 percent from 21.0 to 14.8 BGD. Therefore, we assume that the rate of ground-water depletion in the region fell by about 30 percent from 1.4 BGD to 1.0 BGD.

Third, we again use agriculture's share of total ground-water withdrawals to allocate the change in the stock of ground-water. Continuing with our California example, in addition to the decline in overall ground-water withdrawals, the share of withdrawals attributed to agriculture fell from 86 percent to about 70 percent. Therefore, the rate at which agriculture contributed to the decline in the overall stock of ground-water in the California water resource region fell from 1.2 BGD in 1980 to 0.7 BGD in 1985 (Table 9).

This process leads to some interesting comparisons over time. The change in overall ground-water withdrawals coupled with changes in agricultural uses indicates that by 1990, agriculture's contribution to overall decline in the stock of ground-water declined since 1980 and remained stable since 1985. Regionally, however, there are some differences. For the Lower Colorado and California water resource regions both total ground-water withdrawals and the share of ground-water withdrawals attributed to agriculture has fallen significantly. In both regions, the share of ground-water withdrawals attributed to agriculture has fallen from close to 90 percent in 1980 to about 75 percent by 1990. Much of this decline in ground-water withdrawals can be attributed to the decline in irrigated acres in the Pacific coast over that period. [11] However, for the Missouri Basin, Arkansas-Red-White, and Texas-Gulf, agriculture's share of total withdrawals of ground-water has remained fairly constant since 1980.

Finally, we need to associate values with the estimated changes in the rate of ground-water depletion, We estimate the value of ground-water based on the ratio of energy expenses for on-farm pumping of irrigation water to the estimated amount of water applied to farms from wells. The data on energy expenses and water application is from Farm and Ranch Irrigation Surveys (U.S. Department of Commerce, Census of Agriculture). [12] The values range by water resource region and for 1992 range from $0.10 to $0.12 per 1,000 gallons in California, the Lower Colorado, and the Texas Gulf to $0.07 to $0.09 in the Missouri Basin and the Arkansas-Red-White region. While there is considerable uncertainty regarding the appropriate value of water, the estimates used in this analysis are similar to those used by Grambsch and Michaels (1994). Grambsch and Michaels estimate, based on water price data for the 120 largest metropolitan areas and government capital and operating expenses, was $0.09 per 1,000 gallons. The adjustment to farm income presented in table 9 combines the value of ground-water with the rate of ground-water depletion associated with agriculture. Total damages range from $212 million in 1987 to $291 million 1992.

Impacts on Income

Agriculture affects both production in other sectors of the economy and consumer utility through its use of environmental and natural resource assets. Production in other sectors of the

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[11] Irrigated acres in the Pacific coast fell from 12 million to 10.5 million from 1978 to 1992 (USDA, ERS).

[12] The data in the Census of Agriculture are for 1979, 1984, and 1988. The GDP implicit price deflator is used to match census years with the dates used in this analysis.

economy are affected because changes in environmental assets affect the productivity of other inputs and therefore the cost of producing non-agricultural goods and services. Consumer utility is affected directly through changes in consumption and indirectly through changes in option or existence value.

The approach here is to extend the existing flow-of-output accounts to value environmental goods and services. Double-counting is avoided by recognizing that the inter-industry externalities caused by agricultural production are captured in the existing accounting framework as intermediate expenses in non-agricultural production. Accounting for intermediate external effects is needed only to compute sectoral income. If, however, an accurate measure of national income alone is sought, then intermediate external effects can be ignored. The production externality is an intermediate good whose value is imbedded in the bundle of final goods and services. Agriculture's contribution to the decline in surface-water quality cause a transfer of accounting income from the agricultural sector to the non-agricultural sector of the economy in 1982 of $2.4 billion, in 1987 of $2.7 billion, and in 1992 of $2.7 billion. These adjustments reduce agricultural income and increase income in other sectors of the economy but do not reduce economy-wide NNP. Including intermediate goods in the income accounts is double-counting. Similarly, economic rents generated by a non-market externality are captured in payments to factors of production in the flow-of-income approach. This is not the case, however, when consumer utility is affected directly through changes in consumption and indirectly through changes in option or existence value.

Our estimates suggest only minor adjustments to NNP are made necessary by the effects of agricultural production on the environment and natural resource base. This result follows partly from agriculture's small share (less than 2 percent) of GDP. Even large changes in net farm income have only modest effects on NNP. Adjustments to total farm income and economy-wide NNP for 1982, 1987, and 1992 are displayed in table 10. In each year, total farm income is reduced by about $4 billion when adjustments are made for agriculture's contribution to the decline in surface-water quality and stock of ground-water. Overall, agriculture's contribution to economy-wide NNP falls by $1.3 billion in 1982, $1.4 in 1987, and $1.6 in 1992 when adjustments are made for agriculture's contribution to the decline in surface water quality and stock of ground-water. About 85 percent of the adjustment is caused by agriculture's contribution to the decline in surface-water quality.

The relative effects on net farm product are significantly greater. Adjustments to net farm product range from 6 to 8 percent. The relative share of environmental adjustments to conventional net farm product, however, decreased from 1987 to 1992, Measured agricultural environmental costs per dollar of farm income are declining. This suggests estimated environmental costs flowing from agriculture are not growing as fast as farm income. One possible explanation is policies and programs for controlling soil erosion were effective during this period. In particular, highly erodible acreage enrolled in the Conservation Reserve Program increased from 13.7 to 35.4 million acres from 1987 to 1992. Removing nearly 22 million acres of highly erodible land from production contributed to a nearly 21 percent decrease in estimated soil erosion on cropland during this period even though planted acreage for grains increased by 6 percent. Conservation compliance requirements promulgated under the 1985 farm legislation have provided additional incentives for reducing erosion.

The estimates are consistent with Smith's (1992) work on environmental costing. Smith aggregates the effects of off-site soil erosion, wetland conversion, and ground-water contamination and estimates environmental costs relative to the value of crops produced in 1984. His estimates range from 0.08 to 7.5 percent in the Mountain region to 3.5 to 40 percent in the Northeast. Corn Belt estimates range from 6 to 7 percent. [13]

Our estimated adjustments represent average costs of environmental damages and resource use. Marginal costs are likely to be higher. It is possible that the distortionary effect of commodity

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[13] Smith suggests the work on Viscusi and Magat (1991) on energy implies that the environmental costs of agriculture are comparable to those estimated from several energy sources. Both the Smith and Viscusi and Magat work differ from Nestor and Pasurka's estimates of total value-added for environmental protection of 0.3 percent.

programs is alone sufficient to lead to marginal decreases in social welfare. Accounting for natural resource deterioration and environmental injury, in such a case, would lead to further reductions in social welfare. In addition, our national estimates may be masking significant regional or local problems. Estimated costs of erosion in terms of lost productivity, for example, is not a significant national problem, but may be a significant regional or state problem. Faeth (1993) shows negative net economic value per acre after accounting for soil depreciation and off-site costs for Pennsylvania's best corn-soybean rotation over 5 years. The work demonstrates there may be significant regional variation in resource depreciation and off-site costs of agricultural production.

Summary

Growing interest in the environment has raised questions about the adequacy of current measures of national income particularly when these measures are used as social welfare indicators. The intent of this paper is to more accurately measure agriculture's contribution to national income. Improving the measure of current economic activity requires incorporating non-market final goods and bads into the existing accounts. We focus attention on treating natural capital assets used or affected by agricultural production parallel to how reproducible capital is treated in the national accounts. Net national income and agricultural income are adjusted to reflect the value of changes in the stock of effective farmland, surface-water quality, and ground-water.

We first develop a theoretically consistent framework for incorporating natural capital and environmental goods into the existing income accounts. Next, we apply the framework and adjust agricultural income and national income to reflect the value of the depletion of agricultural natural capital (land and water) and the non-market effects of agricultural production on output in other sectors of the economy and consumers. Specifically, the effects of soil erosion on agricultural productivity and income, the economic effects of decreased surface-water quality, and the depletion of ground-water stocks are presented as examples of the potential scope of accounting adjustments needed in the agricultural sector. Our estimates suggests only minor adjustments to NNP are made necessary by the effects of agricultural production on the environment and the natural capital base. This result follows from agriculture's small share of GDP and because the environmental effects considered in this paper are largely captured in the existing accounts. Adjustments to net farm income are relatively greater and fall in the range of 6 to 8 percent.

Our estimates of "green" adjustments to net farm income are consistent with a view of U.S. agriculture where environmental problems exist and the resource base is depreciating, but the extent of the effects is in the range that can adequately be addressed by thoughtful policy. Our estimates suggest that agriculture's contribution to social welfare far exceeds the environmental damages and deterioration of the stock of natural capital resulting from the production of food.

Estimates of adjusted or "green" income presented here are incomplete. Because the objective of our analysis is to illustrate some of the adjustments necessary to improve NNP and NFP as measures of social welfare, we restrict our scope to consider a few key agricultural effects. Other adjustments, including additional environmental damages and valuing environmental services, are necessary before a credible measure of welfare or sustainability can emerge. We have not, for example, estimated the cost of farm chemical volatilization on air quality, or valued the benefits of landscape preservation or increasing wildlife habitat. In addition, on the cost side, we have not examined how soil quality characteristics, other than erodibility, affect productivity or wildlife habitat. Valuation of farm program benefits warrant further exploration. Program payments are currently treated as income transfers, included in net farm income but excluded from gross farm income. An alternative approach views the Government purchasing environmental benefits like scenic value or wildlife habitat.

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Table 1. Overview of the Existing NIPA Accounts, 1992, $Billion

Flow of Income		Flow of Output	
Compensation of Employees	3,582.0	Personal Consumption Expenditures	4,139.9
Proprietors Income	414.3	Gross Domestic Investment	796.5
Corporate Profits	407.2	Government Purchases	1,131.8
Net Interest	442.0	Net Exports	-29.6
Rental Income	-8.9		
National Income	**4,836.6**	**Gross Domestic Product**	**6,038.6**
		Consumption of Fixed Capital	-657.9
Business Transfer Payments	27.6	Rest of World Net Factor Income	7.3
Individual Tax and Nontax Liability	502.8	Statistical Discrepancy	-23.6
Subsidies Less Government Surplus	-2.7	Business Transfer Payments	-27.6
Consumption of Fixed Capital	657.9	Individual Tax and Nontax Liability	-502.8
Gross National Income	6,022.2	Subsidies Less Government Surplus	2.7
Statistical Discrepancy	23.6		
Gross National Income	6045.8		
Rest of World Net Factor Income	-7.3		
Gross Domestic Product	**6,038.5**	**National Income**	**4,836.7**

Source: Survey of Current Business, 1993.

Table 2. Summary of Farm Income, 1982, 1987, 1992 $Billion

Flow of Income Components	1982	1987	1992
Compensation of Employees	10.2	9.4	11.9
Proprietors Income	24.6	31.3	43.7
Corporate Profits	1.1	1.1	1.0
Net Interest Income	18.1	12.5	10.2
Net Farm Income	**54.0**	**54.3**	**66.8**
Indirect Tax and Nontax Liability	3.3	3.6	4.4
Subsidies Less Current Government Surplus	-2.4	-13.9	-8.4
Consumption of Fixed Capital	22.0	22.0	21.6
Gross Farm Product	**76.9**	**66.0**	**84.4**

Source: Survey of Current Business, various years.

Table 3. Productivity Impacts on Cropland Associated with Soil Erosion, 1982

Region	Sheet and Rill	Wind
	%	%
Northeast	7.1	*
Appalachia	4.7	*
Southeast	1.3	*
Lake States	0.9	0.7
Corn Belt	3.5	*
Delta	1.6	*
Northern Plains	0.6	0.3
Southern Plains	0.2	2.1
Mountain	0.4	1.4
Total	**1.8**	**0.5**

* = less than 0.01%

Source: U.S. Department of Agriculture, The Second RCA Appraisal.

Table 4. Gross Annual Sheet and Rill Erosion (Cropland and and Pasture/Range)

Region	1982			1987			1992		
	Crop	Pasture	Total	Crop	Pasture	Total	Crop	Pasture	Total
	Million Tons			Million Tons			Million Tons		
Northeast	63	5	68	62	5	67	52	4	57
	166	43	209	152	44	197	108	46	154
Southeast	52	4	56	41	3	44	32	3	36
Lake States	124	4	128	118	4	122	99	3	102
Corn Belt	606	45	651	501	37	537	394	34	428
Delta	116	12	128	99	12	444	79	13	91
Northern Plains	256	80	336	224	78	320	189	79	268
Southern Plains	115	149	264	109	143	251	101	129	230
Mountain	91	210	301	84	201	285	66	211	277
Pacific	737	94	167	676	85	152	48	83	131
Total	**1,661**	**647**	**2,307**	**1,474**	**611**	**2,085**	**1,168**	**604**	**1,773**

Source: U.S. Department of Agriculture. Soil Conservation Service.

Table 5. Off-Site Damages Associated with Soil Erosion, 1982

Region	Industry	Consumer	Total
	$/ton		
Northeast	3.74	2.66	6.40
Appalachia	0.96	0.32	1.29
Southeast	1.74	0.00	1.74
Lake States	2.45	0.95	3.40
Corn Belt	0.49	0.55	1.04
Delta	1.97	0.25	2.22
Northern Plains	0.53	0.09	0.61
Southern Plains	1.22	0.61	1.83
Mountain	0.85	0.17	1.02
Pacific	1.39	0.77	2.16
Total	**1.05**	**0.49**	**1.52**

Source: Ribaudo, 1989.

Table 6, Estimated Inter-Industry Annual Soil Erosion Damages

Region	1982		1987		1992	
	$/ton	Million $	$/ton	Million $	$/ton	Million $
Northeast	3.74	255.0	4.47	298.3	5.41	305.5
Appalachia	0.96	200.7	1.15	225.7	1.39	214.6
Southeast	1.74	98.0	2.08	91.5	2.52	89.8
Lake States	2.45	312.0	2.92	355.5	3.54	360.5
Corn Belt	0.49	319.8	0.59	314.8	0.71	303.4
Delta	1.97	252.9	2.36	261.6	2.85	259.8
Northern Plains	0.53	176.3	0.63	200.6	0.76	203.3
Southern Plains	1.22	322.2	1.46	365.7	1.76	405.8
Mountain	0.85	255.3	1.01	288.7	1.23	339.2
Pacific	1.39	231.9	1.66	251.3	2.01	262.5
Total	**1.05**	**2,424.0**	**1.27**	**2,653.7**	**1.55**	**2,744.4**

Table 7. Estimated Annual Consumer Soil Erosion Damages

Region	1982		1987		1992	
	$/ton	Million $	$/ton	Million $	$/ton	Million $
Northeast	2.66	181.0	3.17	211.8	3.84	216.9
Appalachia	0.32	67.4	0.39	75.8	0.47	72.0
Southeast	0.00	0.0	0.00	0.0	0.00	0.0
Lake States	0.95	121.2	1.13	138.1	1.37	140.1
Corn Belt	0.55	359.5	0.66	353.9	0.80	341.1
Delta	0.25	32.0	0.30	33.1	0.36	32.9
Northern Plains	0.09	28.7	0.10	32.6	0.12	33.1
Southern Plains	0.61	162.4	0.73	184.3	0.89	204.4
Mountain	0.17	51.9	0.21	58.7	0.25	68.9
Pacific	0.77	128.3	0.92	139.0	1.11	145.2
Total	**0.49**	**1,132.3**	**0.59**	**1,227.3**	**0.71**	**1,254.7**

Table 8. Ground-Water Withdrawals by Water Resource Region (Billion Gallons per Day)

Region	1980		1985		1990	
	Agriculture	Total	Agriculture	Total	Agriculture	Total
Missouri Basin	11.3	12.0	8.4	9.5	7.4	8.5
Arkansas-Red-White	8.5	9.4	7.0	7.7	6.8	7.4
Texas-Gulf	4.0	5.1	3.7	5.1	4.0	5.5
Lower Colorado	3.9	4.5	2.6	3.3	2.3	3.1
California	18.0	21.0	10.3	14.8	10.8	14.4
Total	**45.7**	**52.0**	**32.0**	**40.4**	**31.3**	**38.9**

Source: Solley, et. al.

Table 9. The Effects of Agricultural Production on Ground-water Storage (Billion Gallons per Day, and Million $ per Year).

Region	1982		1987		1992	
	BGD	Million $	BGD	Million $	BGD	Million $
Missouri Basin	2.1	46	1.5	36	1.4	43
Arkansas-Red-White	3.2	60	2.7	53	2.6	68
Texas-Gulf	2.4	66	2.2	84	2.4	108
Lower Colorado	1.8	46	1.2	24	1.1	46
California	1.2	32	0.7	15	0.7	26
Total	**10.8**	**249**	**8.3**	**212**	**8.2**	**291**

Source: 1980 data from U.S. Department of the Interior, U.S. Geological Survey.

Table 10. Summary of Adjusted National Income and Product Accounts 1982, 1987 and 1992

Income Components	1982	1987	1992
	$ Billions		
Traditional Farm Income	54.0	54.3	66.8
Water Quality			
Industry Transfer	-2.4	-2.7	-2.7
Consumer Effects	-1.1	-1.2	-1.3
Water Quantity	-0.2	-0.2	-0.3
Green Farm Income	**50.2**	**50.2**	**62.5**
Traditional Non-Farm Income	2,468.5	3,638.0	4,769.8
Water Quality			
Industry Transfer	+2.4	+2.7	+2.7
Consumer Effects			
Water Quantity			
Green Non-Farm Income	**2,470.9**	**3,640.7**	**4,772.5**
Traditional National Income	2,522.5	3,692.3	4,836.6
Water Quality			
Industry Transfer	0.0	0.0	0.
Consumer Effects	-1.1	-1.2	-1.3
Water Quantity	-0.2	-0.2	-0.3
Green National Income	**2,521.1**	**3,690.9**	**4,835.0**

Appendix A: Theoretical Model

Definitions

Output of the agricultural sector (q) is given by the production function:

$$q = q(n_1, k_1, Z_1, T_1, eW_1) \tag{A.1}$$

where:

n_1: agricultural labor,
k_1: agricultural capital,
Z_1: environmental input,
T_1: "effective" stock of land used in agricultural production,
e: ground-water extraction rate, and
W_1: stock of ground-water.

Output of the non-agricultural sector (x) is given by the production function:

$$x = x(n_2, k_2, Y, L_2) \tag{A.2}$$

where:

x: non-agricultural good,
n_2: non-agricultural labor,
k_2: non-agricultural capital,
Y: water quality effect on non-agricultural production $(\partial x/\partial Y > 0)$, and
L_2: land used in non-agricultural production.

Household or non-market production (h) is given by:

$$h = h(n_6, x_6, k_6) \tag{A.3}$$

where:

n_6: household labor,
x_6: intermediate inputs used in household production,
k_6: household capital.

The household production function includes non-marketed activities beyond those related to the environment.

The equation of motion for the effective productivity of farmland is

$$\dot{T}_1 = \gamma\left(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1}\right)L_1 - dL_1 \tag{A.4}$$

where land can be managed (improved) by adding labor, intermediate inputs (fertilizer), and capital according to a management function

$$\gamma = \gamma(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1}) \qquad (A.5)$$

where:

γ: is a rate of appreciation,
n_3: labor used in managing land,
x_3: intermediate inputs used in managing land,
k_3: capital used in managing land, and
d: soil erosion rate.

The management function $\gamma(\cdot)$ is assumed linearly homogeneous in its arguments $(n_3/L_1, x_3/L_1, k_3/L_1)$ and in n_3, X_3, and k_3.

The equation of motion for water quality is

$$\dot{Y} = [a - D(Z_1) + \eta(n_4, x_4, k_4)]Y \qquad (A.6)$$

where the impact of agricultural production on water quality is represented by:

$$D = D(Z_1) \qquad (A.7)$$

Water quality can be managed (improved) by adding labor, intermediate inputs, and capital:

$$\eta = \eta(n_4, x_4, k_4) \qquad (A.8)$$

where:

n_4: labor used in managing water quality,
x_4: intermediate inputs used in water quality,
k_4: capital used in managing water quality, and
a: natural repair of water quality.

The damage function $D(Z_1)$ and the repair function $\eta(\cdot)$ are also assumed linearly homogeneous in their respective arguments.

Our equation of motion for the stock of ground-water is

$$\dot{W}_1 = [\psi - e(n_5, x_5, k_5)]W_1 \qquad (A.9)$$

where the extraction of ground-water for use in agriculture is represented by:

$$e = e(n_5, x_5, k_5) \qquad \text{(A.10)}$$

where:

n_5: labor used in extracting ground-water,
x_5: intermediate inputs used in extracting ground-water, and
k_5: capital used in extracting ground-water, and
ψ: the rate ground-water is **replenished.**[14]

As discussed in the text, each natural capital asset is regenerative or renewable but could be exhausted from over-use. The net rate of regeneration, as captured by the equations of motion is a function of the intensity of use, the effectiveness of management to offset the intensity of use of an asset, the level of the stock of the resource itself, and the natural rate of regeneration.

The Model

Social welfare (U) is defined as a function of final goods and services (q, x_2), household production (h), an index of water quality (Y), land in its natural state (L_0), land used in agriculture (L_1), and leisure (n_7). The social planner's goal is to maximize:

$$Max\int_0^\infty e^{-rt} \; U(q, x_2, h, Y, L_0, L_1, n_7)\, dt \qquad \text{(A.11)}$$

where:

q : agricultural output (final good),
x_2: non-agricultural (final) goods and services,
h : household production,
Y : index of water quality, $(\partial U/\partial Y > 0)$ [15]
L_0: unused land (natural state),
L_1: land used in agriculture,
n_7: leisure, and
r: social discount rate

subject to the equations of motion for the stock of effective land, surface-water quality, and the

---

[14] This is a simplified representation. The ground-water replenishment rate ψ is a function of precipitation, inflows and outflows, and the return flow of water extracted for agricultural uses.

[15] Corner solutions are problematic. For perfect water quality human efforts at improvement have no impact. With no water quality agriculture creates no added damages. We assume these situations are unique so that our results are not affected.

stock of ground-water:

$$\dot{T}_1 = \gamma(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1})L_1 - dL_1 \tag{A.12}$$

$$\dot{Y} = [a - D(Z_1) + \eta(n_4, x_4, k_4)]Y \tag{A.13}$$

$$\dot{W}_1 = [\psi - \theta(n_5, x_5, k_5)]W_1 \tag{A.14}$$

In addition to natural capital, there are equations of motion for each of our six types of reproducible capital:

$$\dot{k}_i = I_i - \delta_i k_i \qquad for\ i = 1, \ldots, 6 \tag{A.15}$$

where: I_i represents gross investment in the ith type of reproducible capital and δ_i represents the depreciation rate for each type of reproducible capital.

A materials balance equation and constraints for labor and land complete the model:

$$x(n_2, k_2, Y, L_2) = x_2 + x_3 + x_4 + x_5 + x_6 + I_1 + I_2 + I_3 + I_4 + I_5 + I_6 \tag{A.16}$$

$$N = \sum_{i=1}^{7} n_i \tag{A.17}$$

$$L = \sum_{i=0}^{2} L_i \tag{A.18}$$

The materials balance equation accounts for the output of the non-agricultural sector, x, in the economy. For example, some non-agricultural output goes to final non-agricultural consumption goods and services x_2. Non-agricultural output is also used as investment goods I_i; inputs that go into managing the stock of effective farmland x_3, water quality x_4, and the stock of ground-water x_5; and as inputs in the household production function x_6.

The current value Hamiltonian in flow of output terms is:

$$
\begin{aligned}
H \equiv U\,[&q(n_1, k_1, Z_1, T_1, \theta W_1),\\
&x(n_2, k_2, Y, L_2) - x_3 - x_4 - x_5 - x_6 - I_1 - I_2 - I_3 - I_4 - I_5 - I_6,\\
&h(n_6, x_6, k_6), Y, L_0, L_1, n_7]\\
&+ \rho_3[\gamma(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1})L_1 - dL_1]\\
&+ \rho_4[a - D(Z_1) + \eta(n_4, x_4, k_4)]Y\\
&+ \rho_5[\psi - e(n_5, x_5, k_5)]W_1\\
&+ \sum_{i=1}^{6} \mu_i[I_i - \delta_i k_i]\\
&- \omega[\sum_{i=1}^{7} n_i - N]\\
&- \Omega[\sum_{i=0}^{2} L_i - L] \qquad \text{(A.19)}
\end{aligned}
$$

where ρ_i, μ_i, ω_i, and Ω_i are co-state variables.

The Measurement of Net Welfare

The Hamiltonian along the optimal trajectory is the national welfare measure in utility terms (Mäler, 1991; Hung, 1993). The linear approximation of the Hamiltonian along the optimal path is the exact correspondence to the net national welfare measure. It measures the current utility of consumption (of goods and services and environmental services) and the present value of the future utility stream from current stock changes. This follows because stock prices measure the present value of the future contribution to welfare from a marginal increase in the stocks.

Net welfare is measured as

$$\begin{aligned}
NWM = {} & \frac{\partial U}{\partial q}\left[\frac{\partial q}{\partial n_1}n_1 + \frac{\partial q}{\partial k_1}k_1 + \frac{\partial q}{\partial Z_1}Z_1 + \frac{\partial q}{\partial T_1}T_1 + \frac{\partial q}{\partial W_1}W_1\right] \\
& + \frac{\partial U}{\partial x_2}\left[\frac{\partial x}{\partial n_2}n_2 + \frac{\partial x}{\partial k_2}k_2 + \frac{\partial x}{\partial Y}Y + \frac{\partial x}{\partial L_2}L_2\right] \\
& - \frac{\partial U}{\partial x_2}[x_3 + x_4 + x_5 + x_6 + I_1 + I_2 + I_3 + I_4 + I_5 + I_6] \\
& + \frac{\partial U}{\partial h}\left[\frac{\partial h}{\partial n_6}n_6 + \frac{\partial h}{\partial x_6}x_6 + \frac{\partial h}{\partial k_6}k_6\right] + \frac{\partial U}{\partial L_0}L_0 + \frac{\partial U}{\partial L_1}L_1 + \frac{\partial U}{\partial Y}Y + \frac{\partial U}{\partial n_7}n_7 \\
& + \sum_{i=1}^{6} \mu_i[I_i - \delta_i k_i] \\
& + \rho_3\left[\gamma\left(\frac{n_3}{L_1}, \frac{x_3}{L_1}, \frac{k_3}{L_1}\right)L_1 - dL_1\right] \\
& + \rho_4[a - D(Z_1) + \eta(n_4, x_4, k_4)]Y \\
& + \rho_5[\psi - \theta(n_5, x_5, k_5)]W_1
\end{aligned} \tag{A.20}$$

Recognizing the relationship between net welfare and net product, equation (A.20) can be viewed as the flow of output or expenditure approach to income accounting. That is, GDP = consumption + gross investment and NNP = GDP - capital depreciation = consumption + net investment. The first line in equation (A.20) represents final expenditures on the agricultural good. We assume all output of the agricultural sector (food) is a final consumption good, thus abstracting from the food processing sector. The second line captures total expenditures on the non-agricultural good x. Some x is, however, used as intermediate goods or inputs into the production of other goods. The expenditures on x that do not represent final consumption are subtracted in the third line of equation (A.20). The second and third line, therefore, capture expenditures on the final consumption of the non-agricultural good.

The fourth line of equation (A.20) captures implied expenditures on the household product, natural-state land, aesthetic farm landscape, water quality, and leisure. The fourth line that contains most of the extensions to the traditional GDP accounts. However, some of these expenditures may already be included in the GDP accounts. For example, government expenditures to improve water quality and explicit expenditures by environmental groups to save natural-state land such as old growth forests already show up in the accounts. The fifth line of equation (A.20) captures net investment in each of the six types of physical capital, while the last three lines report net investment in the three types of natural capital. The gross investment components of these last three lines are also extensions of the GDP accounts.

The first three lines of equation (A.20) and the gross investment components of line 5 sum to the traditional measure of GDP. Adding line 4 and the gross investment components of lines 6, 7, and 8 gives the extended GDP measure. Lines 1, 2, 3, and 5 sum to the traditional NNP measure. The entire expression given by equation (A.20) represents the extended NNP measure.

Two final observations stemming from equation (A.20) are worth noting. First, concern for sustainability and properly valuing natural resource depletion leads to extending the accounts by including lines 6, 7, and 8 of equation (A.20). Second, concern with including “non-market” goods (e.g. housework, land in its natural state, rural landscape, water quality, and leisure) in the accounts leads to expanding the accounts by including line 4.

Appendix B: The Optimality Conditions

The optimality conditions are obtained by partially differentiating the Hamiltonian (equation A.19) with respect to the control and state variables. The control variables are the seven uses of labor, the uses of the manufactured output x, gross investment in the six type of reproducible capital, the three uses of land, and the level of water pollution, Z_1. For labor, the optimality conditions are:

$$\frac{\partial H}{\partial n_1} = \frac{\partial U}{\partial q}\frac{\partial q}{\partial n_1} - \omega = 0 \tag{B.1}$$

$$\frac{\partial H}{\partial n_2} = \frac{\partial U}{\partial x_2}\frac{\partial x}{\partial n_2} - \omega = 0 \tag{B.2}$$

$$\frac{\partial H}{\partial n_3} = \rho_3\frac{\partial \gamma}{\partial n_3} - \omega = 0 \tag{B.3}$$

$$\frac{\partial H}{\partial n_4} = \rho_4\frac{\partial \eta}{\partial n_4}Y - \omega = 0 \tag{B.4}$$

$$\frac{\partial H}{\partial n_5} = \frac{\partial U}{\partial q}\frac{\partial q}{\partial e}\frac{\partial e}{\partial n_5}W_1 - \rho_5\frac{\partial e}{\partial n_5}W_1 - \omega = 0 \tag{B.5}$$

$$\frac{\partial H}{\partial n_6} = \frac{\partial U}{\partial h}\frac{\partial h}{\partial n_6} - \omega = 0 \tag{B.6}$$

$$\frac{\partial H}{\partial n_7} = \frac{\partial U}{\partial n_7} - \omega = 0 \tag{B.7}$$

Equations (B.1), (B.2), and (B.6) indicate the value of the marginal product of labor is equalized across the three production sectors. This value ω, the shadow wage rate, is also the marginal value of leisure, equation (B.7), and the marginal value of labor in enhancing land, equation (B.3), repairing water quality, equation (B.4), and depleting ground-water stocks, equation (B.5).

The manufactured good x can be directly consumed (x_2), used as intermediate input or for investment. The optimality conditions for x as an intermediate input for improving land, water quality, and depleting ground-water stocks are:

$$\frac{\partial H}{\partial x_3} = -\frac{\partial U}{\partial x_2} + \rho_3 \frac{\partial \gamma}{\partial x_3} = 0 \qquad \text{(B.8)}$$

$$\frac{\partial H}{\partial x_4} = -\frac{\partial U}{\partial x_2} + \rho_4 \frac{\partial \eta}{\partial x_4} Y = 0 \qquad \text{(B.9)}$$

$$\frac{\partial H}{\partial x_5} = \frac{\partial U}{\partial q}\frac{\partial q}{\partial e}\frac{\partial e}{\partial x_5} W_1 - \frac{\partial U}{\partial x_2} - \rho_5 \frac{\partial e}{\partial x_5} W_1 = 0 \qquad \text{(B.10)}$$

These conditions show that the value of the marginal product of the manufactured good in each of its intermediate uses must equal $\partial U/\partial x_2$, the opportunity cost of direct consumption.

The optimality conditions for x as investment in reproducible capital are:

$$\frac{\partial H}{\partial I_i} = -\frac{\partial U}{\partial x_2} + \mu_i = 0 \qquad (i = 1,\dots,6). \qquad \text{(B.11)}$$

As with intermediate goods, the marginal value of investment in each type of capital (μ_i) must equal the marginal value of the consumption good x_2 ($\partial U/\partial x_2$).

Partially differentiating with respect to each land type determines the distribution of land across sectors:

$$\frac{\partial H}{\partial L_0} = \frac{\partial U}{\partial L_0} - \Omega = 0 \qquad \text{(B.12)}$$

$$\frac{\partial H}{\partial L_1} = \frac{\partial U}{\partial L_1} + \rho_3[\gamma(\cdot) - \frac{\partial \gamma}{\partial A}\frac{n_3}{L_1} - \frac{\partial \gamma}{\partial B}\frac{x_3}{L_1} - \frac{\partial \gamma}{\partial C}\frac{k_3}{L_1}] - \rho_3 d - \Omega = 0 \qquad \text{(B.13)}$$

where A = n_3/L_1, B = x_3/L_1, and C = k_3/L_1. Because γ is assumed homogeneous of degree 1 in A, B, and C, equation (B. 13) reduces to:

$$\frac{\partial H}{\partial L_1} = \frac{\partial U}{\partial L_1} - \rho_3 d - \Omega = 0 \qquad \text{(B.14)}$$

The remaining use of land, L_2, is chosen so that

$$\frac{\partial H}{\partial L_2} = \frac{\partial U}{\partial x_2}\frac{\partial x}{\partial L_2} - \Omega = 0 \qquad \text{(B.15)}$$

Recall the unique character of each type of land. Land in its natural state, L_0, has only a direct welfare effect and no productivity effect. Land used in non-agricultural production, L_2, affects welfare indirectly as an input in production. Farmland, L_1, however, has both a productivity effect in agriculture and a direct welfare effect in utility in terms of providing rural landscape.

The shadow value Ω gives the price of land in its natural state. This price exceeds the direct marginal contribution of farmland to welfare because some farmland erodes, while pristine land and non-agricultural land are assumed not to erode. This price Ω also equals the value of the marginal product of land in the non-agricultural sector.

An additional control variable to consider is Z_1, the environmental input to agricultural production. The optimality condition for this variable is:

$$\frac{\partial H}{\partial Z_1} = \frac{\partial U}{\partial q}\frac{\partial q}{\partial Z_1} - \rho_4\frac{\partial D}{\partial Z_1}Y = 0 \qquad \text{(B.16)}$$

Here the choice of Z_1 can be interpreted as the optimal use of an environmental input, water quality. Equation (B.16) indicates that the value of the marginal product of water pollution in agricultural production is equal to the marginal change in welfare from increasing water quality.

The optimality conditions associated with the state variables describe the choice of stock levels for the six types of physical capital and the three types of natural capital. For the physical capital variables, the optimality conditions are

$$\frac{\partial U}{\partial q}\frac{\partial q}{\partial k_1} = (r + \delta_1)\mu_1 - \dot{\mu}_1 \qquad \text{(B.17)}$$

$$\frac{\partial U}{\partial x_2}\frac{\partial x}{\partial k_2} = (r + \delta_2)\mu_2 - \dot{\mu}_2 \qquad \text{(B.18)}$$

$$\rho_3\frac{\partial \gamma}{\partial k_3} = (r + \delta_3)\mu_3 - \dot{\mu}_3 \qquad \text{(B.19)}$$

$$\rho_4\frac{\partial \eta}{\partial k_4}Y = (r + \delta_4)\mu_4 - \dot{\mu}_4 \qquad \text{(B.20)}$$

$$\frac{\partial U}{\partial q}\frac{\partial q}{\partial e}\frac{\partial e}{\partial k_5}W_1 - \rho_5\frac{\partial e}{\partial k_5}W_1 = (r + \delta_5)\mu_5 - \dot{\mu}_5 \qquad \text{(B.21)}$$

$$\frac{\partial U}{\partial h}\frac{\partial h}{\partial k_6} = (r + \delta_6)\mu_6 - \dot{\mu}_6 \qquad \text{(B.22)}$$

These conditions demonstrate that the value of the marginal product of reproducible capital in each activity (including land enhancement, water quality repair, and diminishing ground-water stocks) is equal to a rental price of capital. Because the investment good is treated as the undifferentiated intermediate good, $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6$. However, the rental prices may differ because of different economic depreciation rates.

The final optimality conditions involve our natural capital stocks: effective farmland, water quality, and ground-water stocks. These conditions are:

$$\frac{\partial U}{\partial q}\frac{\partial q}{\partial T_1} = r\rho_3 - \dot{\rho}_3 \qquad \text{(B.23)}$$

$$\frac{\partial U}{\partial Y} + \frac{\partial U}{\partial x_2}\frac{\partial x}{\partial Y} = (r\rho_4 - \dot{\rho}_4) - \rho_4[a - D(Z_1) + \eta(n_4, k_4, x_4)] \qquad \text{(B.24)}$$

$$\frac{\partial U}{\partial q}\frac{\partial q}{\partial W_1}e = (r\rho_5 - \dot{\rho}_5) - \rho_5[\Psi - e(n_5, k_5, x_5)] \qquad \text{(B.25)}$$

Equation (B.23) has a straight forward interpretation as rental price of effective farmland.

Unlike the conditions for physical capital stocks, equation (B.23) does not have a depreciation rate. Soil erosion, which is similar to a physical depreciation rate, is already captured in equation (B.23). The optimality condition for the stock of water quality is also a rental rate similar to those for physical capital. However, given the form of equation (B.24), this rental rate is adjusted for water quality appreciation rather than depreciation.

Finally, it is interesting to compare the shadow values for reproducible capital to natural capital. For example, a unit of reproducible capital that is used to in the agricultural sector has a value:

$$\mu_1 = \frac{\frac{\partial U}{\partial q}\frac{\partial q}{\partial k_1}}{(r + \delta_1)} + \frac{\dot{\mu}_1}{(r + \delta_1)} \tag{B.26}$$

or

$$\mu_1(t) = \int_t^{\infty} e^{-(r + \delta_1)(s - t)} \frac{\partial U}{\partial q}\frac{\partial q}{\partial k_1}(s)\, ds \tag{B.27}$$

In other words, the value of a unit of reproducible capital in time t is equal to the discounted value of the future services it will provide in terms of agricultural output. An increase in the discount rate (r) or the rate of depreciation (δ_1) will reduce the value of capital.

Our shadow value of natural capital has similar characteristics. For example, a unit of water quality has a shadow value:

$$\rho_4 = \frac{\frac{\partial U}{\partial Y} + \frac{\partial U}{\partial x_2}\frac{\partial x}{\partial Y}}{[a - D(Z_1) + \eta(n_4, k_4, x_4)]} + \frac{\dot{\rho}_4}{[a - D(Z_1) + \eta(n_4, k_4, x_4)]} \tag{B.28}$$

or

$$\rho_4(t) = \int_t^{\infty} e^{-[r - a + D(Z_1) - \eta(n_4, k_4, x_4)](s - t)} \frac{\partial U}{\partial Y} + \frac{\partial U}{\partial x_2}\frac{\partial x}{\partial Y}(s)\, ds \tag{B.29}$$

For natural capital, an increase in the natural rate of regeneration or an increase in human attempt to improve the quality of water reduces the discount rate and increases the shadow value associated with water quality. In addition, unlike reproducible capital, the shadow value captures the discounted value of water quality to both consumers $(\partial U/\partial Y)$ and producers of the manufactured good $[(\partial U/\partial x_2)(\partial x/\partial Y)$.

Some Issues Related to Ecological and Economic Modeling of Ecosystem "Landscapes"

Nancy Bockstael and Jackie Geoghegan

Discussion paper for 1994 AERE Workshop Participants

In this discussion paper are outlined some of the issues and problems we are encountering in a multidisciplinary (ecological and economics) research endeavor sponsored by EPA. The "vignettes" that follow correspond to sections of our presentation and are supplied here in hopes of stimulating discussion and some good ideas. After a brief description of the project, we address each of the following topics in turn:

- the general structure of an ecological-economic model
- the treatment of spatial data in economic analysis
- modeling landscape reconfiguration.

Overview of Project

This work is sponsored by EPA's OPPE (Mary Jo Kealy and Michael Brody, project officers.) The researchers include ecologists from the Center for Estuarine and Environmental Studies, U. of Maryland (R. Costanza, W. Boynton L. Wainger) and economists from the Department of Agricultural and Resource Economics (N. Bockstael, I. Strand, J. Geoghegan K. Bell).

The immediate goal of the project is to model the spatial configuration and dynamic evolution of an ecological landscape by capturing ecological fictions, human behavior, and their interaction. This will provide a means of describing the evolving landscape under different policy scenarios on land use controls, non-point source pollution regulations, etc. Also, the effort may ultimately provide some insights into the valuation of ecosystems - and even the much debated issue of sustainability, although neither of these topics will be given much attention here.

The watershed chosen for the case study is the Patuxent watershed in southern Maryland, one of the nine river basins of the Chesapeake Watershed and covering about 1,000 square miles. This includes parts of seven counties, ranging from the Washington DC suburbs and the state capital to predominantly rural counties at varying stages of development. Significant portions of land within the area are dedicated to each of the major land uses - commercial, high/medium/low density residential, agriculture (mainly cropland and pasture, with few orchards), forests (both deciduous and coniferous), and wetlands. There are a few industrial centers and some military establishments. It is worth noting that agriculture comprises 32% of the watershed's land and forests comprise 46%.

We begin with a very cursory description of a generic ecological landscape model developed by Costanza and Maxwell (1991), because it serves as the starting point for the research effort. The term “landscape” model which we use throughout has come to mean a spatially-articulated dynamic model of an area of land. Traditional ecological studies, similar to traditional economic studies, assumed that systems and actors were spatially homogeneous Landscape ecology is an outgrowth which analyzes and interprets landscape heterogeneity and spatially explicit ecological processes (see Turner and Gardner, 1991). In our subsequent discussions we will be focusing on the economic issues, but it is the landscape nature of the ecological model that has led us in the particular direction we are taking. In fact, we propose a development parallel to that from conventional to landscape ecology for economic modeling.

Serendipitously, the approach taken in the landscape ecology model of Costanza and associates' is particularly close in spirit to one which seems appropriate for economic land use problems. Analogous to the generic ecosystem model that predicts expected changes in habitat conditions, with inter-cell flows of hydrological information linked with physical and chemical parameters, we are interested in predicting expected changes in land use, with inter-cell flows of economic information of spatial and aspatial variables.

A compelling feature of this model is that it is designed to simulate a variety of ecosystem types with a fixed model structure. While the structure is general, however, different sets of ecosystem functions are activated for any site in the landscape, depending on its location and ecosystem type. Additionally, parameters of these functions are specific to the ecosystem type and site and are derived from field data. The underlying model structure is more complex than any particular application is likely to need, but allows for selection among functions and aggregation over levels of detail where applicable. The generic approach is appealing because it is an efficient way to construct models of this sort. Recalibration for a particular ecosystem is time consuming, but not so costly as reinventing the entire model. Additionally a sort of comparability and uniformity across applications becomes possible. Differences in results can be attributed to differing ecological conditions rather than modeling idiosyncrasies.

An important feature of the generic model is its spatial disaggregation. In broad terms, the model operates by dividing the landscape into cells and modeling the ecological functions within each cell and the vertical fluxes of mass above and below sediment. The horizontal mass fluxes of water, soil and nutrients between cells are then simulated over time using a spatial dynamic simulation program. The model is driven largely by hydrological algorithms (varying depending on the ecosystem type) and focuses predominantly on the responses of macro- and microphytes to nutrient availability, light, temperature, water availability, etc. Approximately 14 sectors (including a number of state variables) are incorporated, such as the inorganic sediments sector, dissolved phosphorus sector, hydrologic sector, macrophyte sector, etc. (see Table 2). The Patuxent application of the model focuses on nutrient and sediment loading in the watershed and predicts such things as changes in water quantity and quality, vegetation and amount and quality of wildlife habitat, all at a spatially disaggregated level.

The ecosystem functions and the parameters of those functions that are simulated for any given cell in the landscape are dictated by the cell's "land use" or "habitat" designation at the beginning of any simulation round. Then conditioned on that land use and the stocks of the state variables at that point in time in the cell, the processes and fluxes are calculated. Conceptually, there are two "levels" at which human behavior could be expected to affect this simulation. One is in the land use designation of a cell; the other is in the nature of ecological processes that occur within a cell conditioned on its land use.

Understandably, the ecosystem model without economic input, imposes rather than models this human behavior. Consider the land use designation. The ecological model calculates land use designation through a "habitat switching" model which determines when through natural succession or weather-driven ecological catastrophe (e.g. flood, forest fire), the habitat shifts from one type to another. Human instigated land use changes must be imposed exogenously and hypothetically. Perhaps the most important contribution of the economists will be to model this human land use conversion and how it is related to both the ecological and economic features of the landscape.

Human interactions with the environment conditioned on land use, are similarly imposed in the current ecological model, which uses something akin to a fixed coefficient technology to capture these. For example, if a cell is designated as being in cropland, then a given set of processes and parameters are assumed to operate, conditioned on ecological features such as slope/soil type. Variation across individuals or responses to external stimulae, like changing prices, are ignored. In order to assess the effects of some non-point source policy, the model must impose an assumed change in these processes and parameters, ignoring human response to the change in the regulatory environment. The second type of contribution that the economists can make is in modeling these conditional human interactions. Our first endeavor of this sort involves modeling farmer's behavior, both in crop choice and best management practices adoption, as functions of ecological and economic forces. We anticipate that a transportation sector or a residential sector might follow.

The General Structure of the Integrated Model

The shortcomings of an ecological model with no "moving economic parts" are obvious to economists. The shortcomings of our own treatment of ecosystem-related problems should be equally obvious. While we are not primarily interested in valuation here, how economists have treated ecosystem valuation is relevant to the discussion. With the exception of a few who have written largely in conceptual terms, most economists have been forced to consider only those services of ecosystems that are well-defined, are easily measurable using conventional market or non-market valuation methods, and have immediate consequences for humans. Piecemeal valuation of this sort ignores the more subtle, long range contributions of the ecosystem to human welfare; and it ignores the importance of the configuration of the ecosystem landscape in determining its value, Where things are matters. Analysis that ignores spatial location and spatial arrangement misses important dimensions of the problem. One way of thinking about ecosystem valuation might be: how do we value the reconfiguration of the landscape in its various states as it evolves over time?

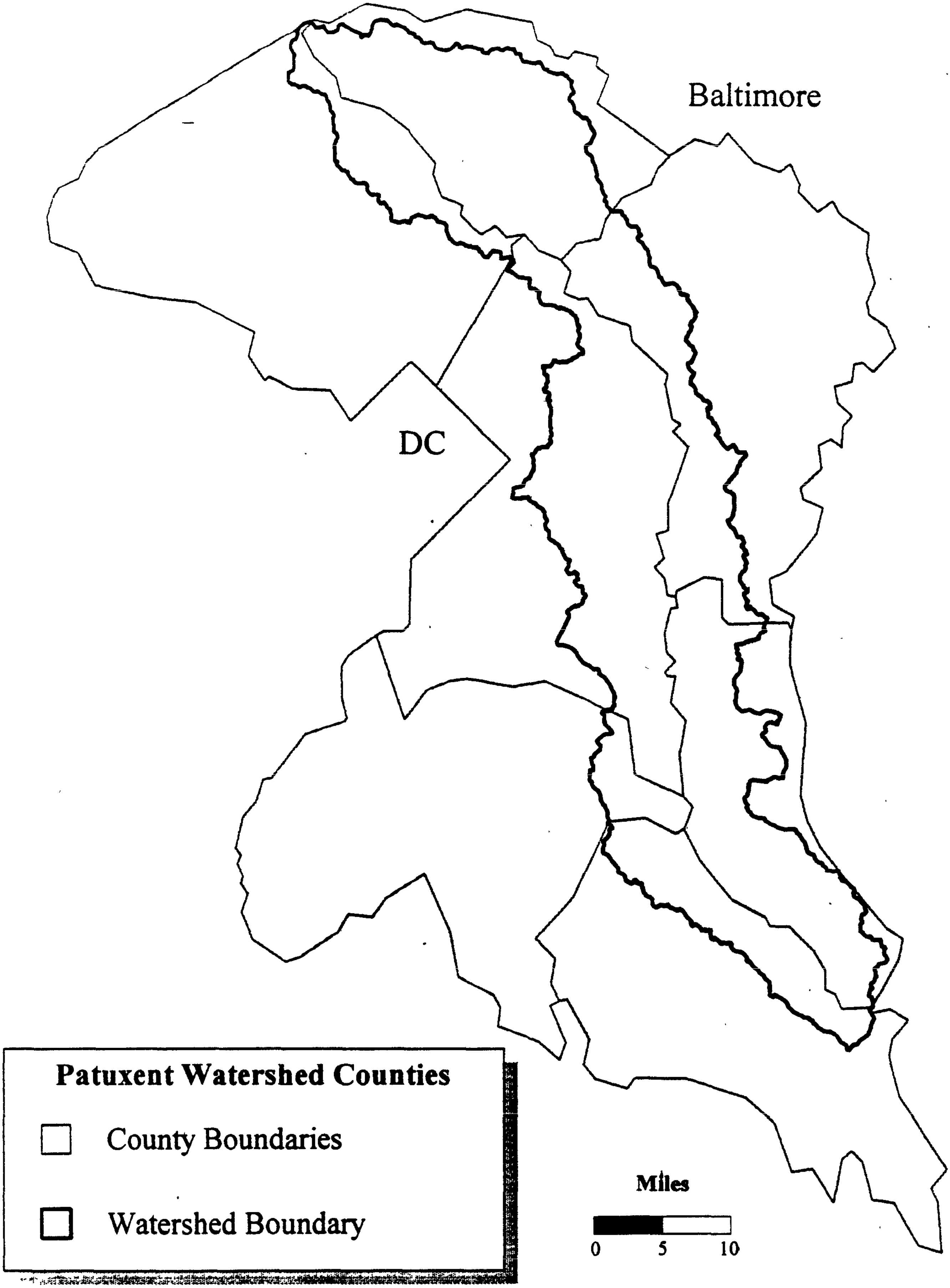
The appeal of a joint modeling effort that looks at the interaction of ecological processes and economic behavior in a spatially disaggregate framework as it plays out over time seems self-evident. The pressing question is how to structure such a modeling effort. Simply put the purpose of having an integrated model is to capture how the distribution of human activities (farming, electric power generation, commercial and residential development, recreation wastewater treatment highway construction fishing) affect the ecosystem as well as to capture the effect of the ecosystem landscape on the quality and value of goods and services (e.g., recreation, wildlife enjoyment water quantity and quality, housing environmental aesthetics, etc.) and, therefore on human decisions. The model needs also to capture how human activity and its impact on the ecosystem may differ under different regulatory regimes.

But an integrated model need not be a “black box”. At this point we do not intend to meld both ecological and economic models into one “super-model.” Instead, we plan for the two types of models to exist in parallel but to exchange information on ecological and . economic elements generated by the other. This approach preserves the integrity and intuition of both models. It also allows the appropriate choice of time step, geographical scale, and level of aggregation which might differ between the ecological and economic models. The inconsistencies that are likely to arise in these dimensions are worth discussing because they pose problems in information exchange, no matter how the integration is structured.

Boundaries

By design the ecological model establishes physical boundaries. From the start the ecologists wanted agreement on these physical boundaries since these determine how many cells and of what types must be covered in their model. For them, the area of interest ranges from the tops of the trees to the depths of the groundwater and extends up to the limits of the drainage basin. The economists had no particular problems with the vertical boundaries (except to the extent that air quality issues of certain types maybe omitted from consideration). However, there is no reason to expect that the drainage basin of the Patuxent is a meaningful economic boundary. The question from our perspective has to do with the extent of relevant markets, and the relevant markets will belabor and land markets and possibly markets for products of the area-principally agricultural, forest and recreational products.

Market boundaries are largely undefinable and sometimes are not related to space at all. However the markets we are interested in - land, labor, recreation and products that have high transportation costs or are perishable-are likely to peter out or dissipate with distance. Regional economic modeling deals with these artificial boundaries of markets, and generally does sousing political boundaries. The attached map shows the difference between the county boundaries and the watershed boundaries, but both are clearly arbitrary delineations


Baltimore
DC
Patuxent Watershed Counties
County Boundaries
Watershed Boundary
Miles
0
5
10

from an economist's perspective. The boundary definition affects what explanatory variables are considered endogenous to the system (and thus must be predicted internally by the model for any scenario simulation) and what variables are considered exogenous to the system (and thus must be predicted by some model of the regional economy). The problem is more complicated than our usual economic intuition would suggest because we are not dealing with aggregates within and outside our region, but with spatially disaggregated decisions that are probably serially correlated over space (more about this in the next section.) Decisions made at point x in the landscape may be affected by characteristics of the landscape within y miles of the spot. Thus if we are interested in simulating activity in the watershed we may need to know about activity that extends some y miles beyond the watershed boundaries -or up to some natural geographic barrier such as an ocean major river, etc. Because our GIS data is available by county, we currently have information that extends up to the political boundaries in the attached map. This poses no problem for information exchange between the two models, since the ecological model will use only that part of our information which it needs. But the "sliding" boundary problem remains an issue for the internal workings of the economics model.

Organizational Complexity

The ecological model is structured around a desired level of ecological complexity and resolution. It simulates the activities of thirteen sectors and tracks twenty-five state variables all of which are listed in Table 2. Modeling with greater levels of disaggregation is possible, but costly, and requires a significant amount of additional data collection and programming. However, many of the state variables of importance for tracking ecological processes are not of direct interest to the modeling of human behavior (or for assessing the value of the landscape configuration).

Unfortunately, the ecological model cannot afford much detail in the state variables that are most visible and important to humans. The animal kingdom is represented by one state variable "consumers" and the macro-plant kingdom by the state variable, macrophytes levels of aggregation decidedly unacceptable to the economists. A proposed solution is to introduce the details exogenously by determining in side calculations the subgroups of macrophytes and consumers that are likely to be found in a given cell depending on its habitat/land use type, surrounding land uses and distances to critical ecological features (streams, etc.) and human disruptions (highways, etc.) The model will include markers and detailed rules for species loss, treating habitat evaluation as a side calculation. A function will be developed that will indicate the likelihood of game species and other forms of wildlife in particular habitat types. This approach allows for the provision of additional complementary information without increasing the level of disaggregation of the generic ecosystem model.

Time Scale

The ecosystem model operates on a time scale of a day or less. Yet, given available data the economic models will be estimated on an annual basis. This means that the timing of the exchange of information and the time-dependent nature of that information must be carefully thought out. The economic decisions can be modeled on an annual basis but then distributed over the year according to rules or separate side calculations. For example, intra-year timing of the agricultural decisions will be easy to predicts, since these are governed by growing seasons. The timing of those decisions that are prompted by weather can be driven by the ecological simulation that incorporates weather pattern simulations as well.

Land conversion decisions cause more trouble. Their timing is important because construction can have different immediate ecosystem impacts depending on the season. One solution is to use independent data on building starts and construction durations to forecast the seasonal impacts of construction. We may also add another habitat/land use type- land in transition, since this state can cause more sediment loss than almost any other.

Geographical Scale

The geographical scale of resolution between the two models will also differ. The ecosystem model divides the study area into cells each covering approximately 0.364 km^2 or 90 acres. But for land use conversion decisions in states like Maryland, 90 acres is far too large relative to the decision unit. We have a choice (described in a later section) of using actual ownership parcels or of dividing the landscape into calls but the cells would likely be smaller than 90 acres and more closely matched the size of areas that are observed to convert in a given year.

In any event, the economic model will need to use observational units smaller than the cells in the ecological model and this poses one of the more serious modeling conflicts for the project. The economic model of land use conversion will generate predictions at a higher level of spatial resolution than the ecological model will need. However, since the former is likely to take the form of a discrete choice model it will produce predicted probabilities that can be interpreted as proportions. The ecological model can accommodate heterogeneity in the form of shares) within a cell if it is not necessary to preserve information on the specific locations of the heterogeneous factors within the cell. Devising weights to monitor what is happening in cells, thresholds can be set so that cells could go from homogeneous to heterogeneous units and vice versa. This additional detail will also allow the model to make inferences on a wider variety of land use restrictions (i.e., agricultural policies, zoning policies, and environmental protection policies).

Disaggregating the output from the ecological model for use in the economics model may be more difficult. The exact locations of some features of the landscape that are important to economic decisions will be known independently and will be unchanging (e.g. location of streams) but information about others (e.g. quantity and quality of stream flow) will be available only as output from the ecological model. We do not yet know how serious a problem this will turn out to be.

Time Horizons

Some ecosystem effects of human actions take a long time to play out, and as a consequence the ecologists are interested in scenarios of at least 20 years. A time horizon of this length makes economists nervous - so much that affects human behavior (technology, changing preferences, . . .) is impossible to predict very far in advance. Nonetheless, we have agreed to 20 year scenarios, but there will be an array of these subject to a host of different assumptions.

Spatial Data/Issues in Economics

The emphasis in the discussion so far has been on “space” and “time”. If “ecological-economic” modeling has any meaning at all, it must have something to do with the interactions between humans and natural systems over space and time. Economists have excelled at modeling time dynamics, but spatial issues have received much less attention. Perhaps this is because the markets for most goods are not spatially driven. Land, while not the only exception, is certainly the most obvious one.

What happens to land, not just aggregate land but the spatial arrangement of land, is a topic of increasing interest to multiple disciplines. Land use is inextricably tied to public infrastructure demands that are more or less costly depending on their spatial distribution. Land use is almost synonymous with locational externalities - visual, noise, etc. And land use has environmental consequences that differ markedly depending on the pattern of remaining habitat and the size and proximity of disturbances to ecologically sensitive areas. The configuration of land is one of the major contributors to the quality of life.

Yet, traditional fields of economics have reduced the complexity of spatial relationships, almost to the point of making spatial issues non-issues. Either aggregate relationships have been specified or the spatial components in a model have been reduced to uni-dimensional variables, e.g. the distance between economic activities in a location model, the wage differential in a migration model, cost of access in a transportation mode choice model. The concept of a landscape *mosaic* of natural and human-managed patches is foreign to economists.

Data drives analyses. In the absence of spatially articulated data, there has been no impetus to develop broadly adopted methods for analyzing two dimensional space. But now that GIS data is becoming more readily available, economists are reconsidering their analytical tools. Along with others at a similar stage of thinking, we are looking for away to take full advantage of this new type of data. Is there some way of explicitly thinking about spatial interactions and their impacts on decision making beyond including location specific amenities and distances to features of importance? Can we model these spatial issues using higher dimensions in order to increase the predictive power of our model? If not a totally new approach, can we use these new data to better describe the aspects of space that matter?

While most economists know that GIS is a technology that can store, analyze, and display spatial and descriptive data, not so many economists have had the opportunity to work with such data. A GIS technology takes information from existing maps or aerial photographs and digitizes it, keying points, lines or polygons in one way or another to map coordinates. GIS software is used to manage the database system to store and retrieve data to analyze data and to report analyses and display maps.

Our GIS data includes mappings of land uses at four points in time for the counties of interest. We also have, or will soon have, access to digitized maps of ecological features, such as slopes, soil types, elevations, and hydrology (streams, rivers, etc.), as well as the output of the ecological model simulations that will provide values for state variables in a GIS format. We expect to obtain GIS data on zoning and land use controls in our counties, as well as likely scenarios for future land use management. Additionally, our data base includes transportation networks, business districts, street addresses, etc. The latter allows us to match information from other sources (including a tax assessment data base and a survey of farmers) to map coordinates. GIS software provides a means of obtaining a variety of measures, including calculating distances, registering contiguous attributes, and measuring percentages of areas of various shapes and sizes made up of different attributes.

While we are still searching for the most valuable way to use these data there are some spatial attributes that are clearly of importance to the value of land in different uses, For example, the value of a parcel in residential use will be affected by access to employment centers (given by transportation networks and proximity to business districts) and private and public infrastructure (shopping, schools, recreational facilities), etc. But it will also be affected by the spatial arrangement of ecological features and man-made structures making different parcels equi-distant from employment centers of differing value because of these spatially oriented amenities/disamenities. Additionally, the ability to convert land to a developed use will be circumscribed by regulatory mechanisms and incentives: zoning, land use controls, taxation patterns, best management practice incentives, etc. The value to society of land in an undeveloped state will also depend on attributes of the land and its spatial arrangement. For example, the suitability of a patch for wildlife habitat will depend on its water and vegetative features, its size, shape and habitat edges and its proximity to human disturbances and human access.

Spatial Measures in Modeling

The disciplines of landscape ecology and geography, as well as a sub-field of econometrics called “spatial econometrics” (see, for example, Anselin, 1988) offer interesting alternatives to conventional measurements of space. Here we discuss two types of measures of spatial pattern that have emerged in some of this literature: measures which capture in a two-dimensional way relationships among cells in the landscape and measures that capture the complexity of spatial pattern. We consider their application to economic models that attempt to describe what goes on at any given location in the landscape.

The original motivation for the following measures were driven by regional economic development issues. Therefore, all the following measures were derived in order to use spatial aggregate data, on large spatial units such as counties or census bureau tracts. However, our model will use disaggregate data on much smaller spatial units, such as land parcels, so the following measures will have to be modified to use on disaggregate data. Given this caveat, we now describe some of these measures.

Spatial contiguity matrices describe spatial relationships between all pairs of spatial units in the landscape. The simplest is based on binary contiguity between spatial units, where each cell is represented by a row and a column in a matrix. For any i,j combination of cells a 1 appears as the i,j element of the matrix if the cells are contiguous and a 0 otherwise. This requires dividing the landscape into units, and for regular structures mathematical properties are well defined. It is also possible to define higher order measures of contiguity.

Spatial weight matrixes are extensions of spatial contiguity matrices that add weights to the contiguity measure. Matrices with terms such as the following are commonly employed:

$$w_{ij} = b_{ij} a_i B_{ij}$$

or

$$w_{ij} = \left[d_{ij}\right]^{-\alpha} \left[B_{ij}\right]^{\beta}$$

or

$$w_{ij} = \alpha \exp(-d_{ij} / \beta)$$

where
b_{ij} = binary contiguity factor
a_i = the share of area i in the entire spatial system
Bij = the proportion of the interior boundary of unit i in contact with unit j
d_{ij} = distance between unit i and unit j
and α, β = parameters.

In the first two expressions above, the matrix contains non-zero information only for contiguous cells, although as the third example suggests, weight matrices can easily be defined that allowed relationships with more distant cells. In our disaggregate model, which has much smaller spatial units, these measures can be modified in a number of ways. For example, the' first two measures, which are based on binary contiguity, can be extended to allow for higher levels of contiguity. In this way, land use parcels can be affected by other spatial attributes that are not directly contiguous, but yet are of interest for their potential impact on the land area in question. Measures in the spirit of the third example above already permit impacts from noncontiguous units, so can easily be used to create matrices that incorporate influences from a further distant.

An obvious way to use these matrices in econometric modeling is to add structure to the pattern of correlation among errors. Spatial data introduces the likelihood of spatial autocorrelation. One can also imagine using these weights to discount location-specific explanatory variables with distance. In this context, one might think of these weights as spatial lag operators.

Landscape ecologists have also developed indices of complexity of spatial pattern, derived from information theory and fractal geometry. These indices have been used principally to compare spatial heterogeneity across landscapes of considerable size, but seem adaptable to our type of problem (O'Neill et al 1988). A well-known and commonly used measure of diversity (or conversely dominance) from information theory is applicable here: Within any given sized sub-area of landscape, diversity of land uses could be measured by:

$$H = -\sum_{k=1}^{m} P_k \ln P_k$$

where P_k is the percent of the sub-area in land use k and m is the total number of land uses. H ranges from 0 when all land in the sub-area is of the same land use to ln m, the value of H when all land uses are represented equally. Consequently, a measure of dominance is given by:

$$D = \ln m - H$$

and ranges from 0 to ln m, at maximum dominance.

A second and less well-known information theory measure is a measure of "contagion". This index is concerned with edges and contiguity, and reflects the extent to which land uses are clumped.

$$C = 2n \ln n + \sum_{i=1}^{n} \sum_{j=1}^{n} Q_{ij} \ln Q_{ij}$$

where Q_{ij} is the proportion of cells of type i adjacent to cells of type j and n is the total number of cells in the sub-area. Note that 2n in n is the maximum value of the second term. At high values of C, land uses are highly concentrated; at low values the landscape is heavily dissected.

Finally a measure adopted from fractal geometry is frequently used to capture the complexity of the sub-area. The fractal dimension is twice the slope of the regression line found by regressing the log of one-quarter of the perimeter on the log of the area. The fractal dimension ranges from 1.0 if all patches are simple square shapes to 2.0, which represents an patch with the same area, but with a very complex shape.

In the next section, we explore how we might actually do some economic modeling in space and how we might use some of the above concepts to add richness to our modeling effort.

Modeling Land Conversion

Recognizing that the ecological effects of human activity are driven by the specific uses man chooses to make of the stock of natural capital, one of the major contributions we can make to the ecologists' landscape model is an understanding of how the land use decisions are made by individuals. This is critical for the integrated modeling effort, since the simulation of each geographically designated cell's ecological functions are driven by land use designation.

More specifically, the purpose of this phase of the project is to develop the ability to predict future land use of a parcel or unit of land, given information on its history, relevant zoning and other land use restrictions, the general level of regional economic activity, and the variety of often spatially related economic and ecological variables that affect the value of the parcel in different uses. Given this information, we intend to predict the probabilities that a parcel of land with certain characteristics will stay in its present land use or convert to alternative uses.

There have been numerous attempts by economists to model land use conversion (see, for example, models of urban fringe development by Dunford, Marti, and Mittlehammer, 1985; Alig and Healy, 1987; Barnard and Butcher, 1989; McMillan, 1989) but they have been hampered by limited data. The data we have available, while not perfect, offer the potential for a richer and more spatially disaggregate model than has previously been possible. But as the previous section explains, we are still uncertain as to how to take full advantage of this spatial data.

We have two interesting data sources that contain information on land use conversion. The first consists of snapshots, at four points in time, of land uses in the seven Patuxent watershed counties prepared by the Maryland State Office of Planning. These are GIS data, and in this format different land uses are recorded as polygons on a digitized map. A polygon of a minimum of 10 acres will appear on the map with a separate land use designation. This GIS database allows us to see three periods of land use changes - from 1973 to 1981, from 1981 to 1985, and from 1985 to 1990. The land use designation categories are reported in Table 1, but can be summarized as types of agricultural land, types of forests, types of residential, industrial, institutional or commercial development, barren land, wetlands, etc.

Tax assessment files comprise the second data source of interest and were acquired from Maryland's Department of Assessments and Taxation. These files include observations on each individually or publicly owned parcel of land in the seven relevant counties as of 1993. The database includes fields for a wide range of interesting characteristics of the land parcel and the owner. Not all fields are filled in for all observations or all counties, but there remains considerable information on each parcel. Variables include size, location, zoning, land use designation property factors (e.g. sewer, water, historic, etc.), structure description, market value, tax assessment, building value, land value, etc. Of particular interest to us are the variables that report property transfer information, and year built, if a structure exists on the property. Because the data base includes addresses, we can, at least in theory, map the locations of these parcels onto our GIS database using Census Bureau TIGER files that supply GIS coordinates for street and road addresses. This process is underway and we are currently attempting to resolve the matching problems that invariably occur with such data sets.

These two data sources together provide important information and can be merged in the GIS database, but they are different in a number of important dimensions. The State Office of Planning land use maps give us a good picture of land use change over time. Land use changes are recorded in terms of polygons switching from one land use designation to another, rather than individual parcel owners' decisions. This maybe a useful format if we choose to employ a grid or cell type approach in defining our units of observation. In that case we could model the proportion of each cell in a given land use at a point in time. However, from these maps changes can be observed only in approximately 5 year intends. This obscures observation of the sequencing of changes and lengthens the time unit of measurement even further relative to the ecological model.

In contrast, the tax assessment database is extremely detailed and includes data by parcel of ownership, should we choose to use that as the unit of observation. However, because it records information as of the current period, it must be used creatively to extract information about past changes. These changes must be deduced from information on time and conditions of property transfer, date at which property was converted from one tax category to another, and year structure was built. Additionally, if we have difficulty mapping all parcels, we may encounter selection biases in our sample of observations.

Despite the shortcomings in both data sets, merging them will provide far better information than has been available to analyze land use conversion in the past. At this point we expect that our observational units will be cells rather than parcels, in part because even in the tax assessment data base the observations are based on parcel ownership only in the current time period not at the time the decision was made. Thus, from these data it will be impossible to determine whether several new housing units came from one or more conversion decisions. Economists are more comfortable using observations on decision makers than on units of the commodity, but somewhat related problems arise in some types of surveys. For example, on site surveys in recreation yield samples of trips rather than samples of recreationists.

Also included in the GIS data base is information on transportation networks and central business districts, hydrology (streams, rivers, etc.), land slopes, soil types and elevations. (We are currently attempting to acquire historical transportation information.) This is all in addition to the GIS level data supplied by the ecological model. These data allow us to calculate, for any arbitrarily small cell in the landscape, such things as distances from roads and highways, towns and employment centers, and natural ecological features of interest - like shoreline or recreational facilities. It also provides a means of calculating variables that reflect what is going on around a particular point on the landscape and what may be happening to the quality of the environment.

Two other external sources of information are worth mentioning at this point. The state of the regional economy is likely to be an important factor in determining land use conversion in the Patuxent watershed. In order to simulate future scenarios of land conversion, we need a forecasting model of the economic activity in the region. The most likely candidate for this is a well recognized regional model of Maryland developed and marketed by Mahlon Strazheim of the Economics Department of the University of Maryland.

Another source of externally supplied information will come from the Patuxent Demonstration Project. This is an inter-governmental research group that has assembled the current zoning and land use restrictions for the Patuxent watershed counties in a detailed GIS format. They have also developed a set of potential land use management scenarios that could conceivably evolve over the next two decades in this area. These include zoning based on comprehensive plans and sewer/water service plans; forest conservation and agricultural best management practices programs; and clustering requirements together with urban best management practice programs.

While we have a host of data related problems to overcome, including some potentially serious sample selection problems, our ultimate data set is likely to consist of discrete panel data: time series observations on land use of individual parcels or of equi-sized cells in the landscape. We plan to use models of discrete panel data (see Heckman, 1983) either to predict the probability of any parcel of land, or the proportion of any equi-sized geographic cell, being in a given land use at time t.

Heckman's treatment of panel data incorporates intertemporal connections among decisions and the resulting increased complexity in error structures. Adapting Heckman's general model, we consider that the continuous latent random variable (i our problem reflecting utility or returns from putting parcel *i* in land use *m* at time *t)* can be given by a systematic function of exogenous variables and variables capturing the dynamic nature of the decision (i.e. functions of past decisions and values of past latent variables) as well as an error term.

Heckman frames his problem in a dichotomous choice context, but we will have either polychotomous choices or nested dichotomous choices. In a general model, we would be interested in predicting the probability that a parcel, conditioned on current land use, will end up in any of *m* land uses in the next period, where *m* might be as many as 5 or more land uses depending on aggregation over categories in Table 1. For our particular study area, however, most conversions take place from some relatively undeveloped use (e.g. forest or agriculture) to a developed use (some type of residential or, far less often, commercial). Rather than having a majority of zero cells in a conversion matrix, we might alternatively consider a series of nested dichotomous choices:

1. develop or not

2. if develop residential or commercial
3. if residential: low or high density

Both polychotomous choice and nested dichotomous choice problems are most easily framed in the context of multinomial logit. However, the complicated error structures that are suggested below are not possible in a logit framework unless they can be captured by fixed effect terms.

Dynamic Issues

There are a variety of types of dynamic relationships possible in discrete panel data. First and foremost, the parcel's state in the previous period will be expected to have an effect on the decision. This type of term would appear in a simple Markov chain model. In our problem it is clear that the land use in time t-1 will have an important effect on land use choice in time t, because of inertia and varying costs of transition (none of which are likely to be fully captured with explanatory variables). It is not obvious that choices in time periods t-j, j> 1 can be expected to have a separate effect. The Markov effects may not be stationary, however. They maybe changing overtime because of (otherwise unmeasurable) changes in land use policies, for example.

Additionally the cumulative history of the parcel might matter. For example, the valuation of a parcel in a particular use maybe affected by how long the parcel has been in its current state. Accumulation and depreciation of natural, human, and structural capital, as well as other forms of time dependency, can be reflected this way. "Renewal" terms of this sort may have interesting interpretations in land conversion models related to soil depletion, timber cycles, or depreciation of man-made capital, but whether our data will support such subtleties remains a question.

We might also expect a lagged adjustment to past valuations of alternative states. Given the near irreversibility of some land use conversion decisions, responses to a persistent economic signal are more likely than sudden responses to a one-time change in economic conditions. Additionally, given the time it takes to plan, obtain permits, etc. there will likely be a lag between conversion decision and observable action.

Exogenous Variables and Spatial Issues

The model needs to capture those factors that dictate the value of a parcel of land in different uses. These maybe ecological features of the landscape, such as soil type, slopes, water availability, scenic amenities. They will also include man-made features of the landscape, such as access to employment centers (given by transportation networks and proximity to business districts), and access to both private and public infrastructure (shopping, schools, recreational facilities), etc. The ability to convert land and its ultimate value in alternative uses will be circumscribed by regulatory mechanisms and incentives: zoning, land use controls, taxation patterns, best management practice incentives, etc. But even this relatively straightforward consideration has locational spill-over effects, since the zoning of the land next door has an effect on the value of a particular parcel. Finally, the value of a parcel in a given land use is very much affected by the land uses of surrounding land, not just specific features with point locations.

There are a few ways we could imagine incorporating the spatial measures mentioned earlier into the systematic part of our land use conversion model. A weighting scheme based on distance and contiguity might be used as a spatial lag operator on exogenous variables. For example, instead of using as an explanatory variable equal to the distance to the nearest employment center, we might include all relevant employment centers measured by their size and weight them by the spatial weights (i.e. discount them by distance and/or contiguity.)

We could also apply spatial lag operators to variables that reflected land use, the dependent variable, for surrounding cells. The probability that a particular undeveloped parcel will be developed during time period t will be affected by the land use configuration surrounding the parcel at the beginning of t. We might measure the proportion of land within any concentric circle, for example, in a particular land use, and then weight these measures by the distance of the concentric circle from the parcel and/or by contiguity factors.

These measures are promising but might not fully capture the aesthetic, congestion, access, etc. aspects of land configuration that make location so important in land values. Models of land value or land conversion may make particularly good use of the measures of spatial heterogeneity and complexity that have, up till now, been used principally for description. By choosing an appropriate size for a sub-area, we can calculate measures of diversity, contagion, etc. for circles or squares centered on each cell. By doing so, we encounter the “sliding” neighborhood phenomenon making knowledge of areas within an ever expanding boundary necessary for simulation. This argues all the more strongly for modeling an area bounded by geographical “walls” such as bays, rivers, etc. rather than the boundaries of the watershed.

Error Structure

The error structure in our problem poses particular problems. In his general model, Heckman assumes that the errors are distributed with mean vector zero and covariance, Σ, which is a TxT positive definite matrix. This specification allows non-stationary and serially correlated errors. Although more general than previous models, Heckman’s specification assumes that $\varepsilon(i)$ is independent of $\varepsilon(j), j \neq i$, because he is concerned with panel data in which the cross section observations are taken over randomly selected individuals.

In our case, the observations will be overland parcels and the spatial relationship among parcels is likely to dictate a pattern in the error structure in the cross-section dimension as well as the time series dimension. Perhaps the most obvious use of the spatial contiguity or spatial weight matrices described in the last section is to provide structure for the covariance matrix of the errors. Clearly our model will not capture all relevant factors and the omitted ones will certainly be correlated over space because of the immense importance of locational spill-over effects. The types of weight matrices discussed above can provide structure - dependent on distance and contiguity factors - for the covariance matrix of the errors.

The complexity of the error structure, together with the polychotomous or nested nature of the choice problem, poses estimation difficulties. If we assume a generalized extreme value distribution for the ε's, thus generating a multinomial logit specification then only a fixed effect model is practicable. However, if we wish to represent the likely error structure, we would need to assume a normal distribution (as does Heckman). We have not yet resolved this modeling problem and any ideas will be gratefully received.

Table 1

— The Habitat or Land Use Designation Types

Developed/Urban Land Uses:

- Low density residential
- Medium density residential
- High density residential
- Commercial
- Industrial
- Institutional
- Extractive
- Open urban land

Agriculture:

- Cropland
- Pasture
- Orchards/horticulture
- Row/garden crops

Forest:

- Deciduous forest
- Evergreen forest
- Mixed forest
- Brush

Other:

- Water
- Wetlands (by State Land Use definition; not Section 404 definition)
- Bare ground

Table 2

— State Variables in the Generic Ecosystem Model

Hydrology Sector:
- Surface water
- Unsaturated water
- Saturated water

Hydrodynamic Sector:
- Horizontal Flows (rivers, waves)
- Vertical Flows (snow, rain)

Inorganic Sediments Sector:
- Deposited inorganic sediments
- Suspended inorganic sediments
- Pore space

Salt (NaCl) Sector (Conductivity):
- Salt crystals
- Salt in surface water
- Salt in sediment water

Dissolved Phosphorus Sector:
- Phosphate in surface water
- Phosphate in sediment water

Dissolved Nitrogen Sector:
- Dissolved inorganic nitrogen in surface water
- Dissolved inorganic nitrogen in sediment water

Dissolved Oxygen Sector:
- Dissolved oxygen in surface water

Non-Macrophyte Sector:
- Algae (phytoplankton and/or periphytons)

Macrophyte Sector:
- Macrophyte photosynthetic biomass
- Macrophyte non-photosynthetic biomass

Above Sediment Organic Matter and Detritus Sector:
- Suspended organic matter
- Standing detritus

Organic Sediments/Soil Sector:
- Deposited organic matter

Consumer Sector:
- Consumer biomass (all fauna except microscopic decomposes)

Fire Sector:
- Fire Igniters
- Fire Propagates

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ABSTRACT

Landscapes, Ecosystem Value, and Sustainability

by

Robert Gottfried, David Wear and Robert Lee

This paper offers an ecologically-based view of land and land value, building upon the concepts of ecosystems as multiproduct assets and of landscape ecology.* Having briefly reviewed landscape ecology, the paper questions the ability of markets to create optimal landscapes, even when traditional methods of internalizing externalities are applied. The paper concludes that attempting a complete valuation of ecosystems appears to be a rather quixotic enterprise. Managing natural systems to optimize production of certain valued outputs, perhaps subject to certain sustainability provisions, may represent a more practical goal. Achieving sustainable landscapes, however, requires both sufficient ecological knowledge and institutions capable of bringing about this result inasmuch as the unaided market cannot do so. The paper argues that landscape modeling may help provide needed information, and examines forms of public and private ownership to assess how well particular institutional conditions might facilitate ecological adaptation. Flexibility and creativity will be needed in designing institutions that can deal effectively with landscape-scale management.

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* This paper is the outgrowth of a series of discussions by the authors as part of the US Man & the Biosphere Temperate Zone Directorate Project “Land Use Patterns in the Olympic and Southern Appalachian Biosphere Reserves: Implications for Long Term Sustainable Development and Environmental Vitality.”

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People and Parks: Economic Management of Khao Yai National Park, Thailand

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October 1994

Abstract

Following the policy literature on people-park conflicts, this paper provides an economic analysis of the efficiency of park management decisions and their impact on rural incomes in developing countries. Using Khao Yai National Park (KYNP) in Thailand as a case study, analysis of an economic model reveals the importance of spatial and intertemporal characteristics of land use in and around a park area for establishing management schemes that meet both preservation and rural development goals. Sensitivity analysis of the model reveals the role of discount rates, the importance of habitat size and spatial externalities, and the impact of the perspective of the manager-local, national, international-on optimal land use. The spatial analysis suggests that current management of KYNP fails to consider the impact of the park on economic development in surrounding and, in so doing, allocates too much land to a pure preservation use. A buffer zone policy paired with rights for extractive good collection within the park would increase the social benefits created by KYNP.

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VALUING BIODIVERSITY FOR USE IN PHARMACEUTICAL RESEARCH

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VALUING BIODIVERSITY FOR USE IN PHARMACEUTICAL RESEARCH

Abstract

There has been considerable recent interest in “genetic prospecting" among wild plants and animals for novel chemical compounds. Such prospecting might uncover new pharmaceutical products and provide a mechanism for saving endangered ecosystems. It is unclear what values may arise from such activities, however. Evidence from observed transactions is incomplete. Existing theoretical investigations are flawed in their treatment of the probability of discovery of novel chemical compounds. In this paper we develop a simple model in which the “marginal species” maybe redundant with respect to its potential as a source of new chemical leads. By optimizing the value of the marginal species with respect to the probability with which it yields a commercially successful product we are able to place an upper bound on its value. This upper bound may itself be relatively modest. Slight modifications in assumptions lead to drastic reductions relative to this upper bound. We also extend our findings from the value of the marginal species to that of the marginal hectare of habitat by combining our results with a common model of the species-area relationship. We find that the incentives for habitat conservation generated by pharmaceutical research are also, at best, very modest, and are more likely to be negligible.

Introduction

There has been considerable recent interest in "genetic prospecting." Genetic prospecting is the search for chemicals produced by wild organisms. In nature, these compounds are employed to escape predators, capture prey, increase reproduction, and fight infection. These chemical compounds might be of considerable commercial value if adapted to industrial, agricultural, and, particularly, pharmaceutical applications.

Genetic prospecting has also been touted as a tool for the conservation of biodiversity. It has been argued that incentives for the preservation of areas m which genetic diversity is greatest, particularly tropical rain forests, might be increased if landholders could be compensated for the values generated by endangered organisms used in new product research (this argument has been made, with varying degrees of enthusiasm, by, among others, Farnsworth and Soejarto, 1985; Principe 1989: Wilson, 1992; Reid *et al*, 1993; and Rubin and Fish, 1994).

In order to determine the strength of such conservation incentives, we would need to know the value of the "marginal species"[1] in genetic prospecting. A number of studies, including those of Farnsworth and Soejarto [1985], Principe [1989] McAllister [1991], Harvard Business School [1992], Pearce and Puroshothamon [1992], and Aylward [1993][2] have adopted, with differing degrees of sophistication, a straightforward approach to valuing biodiversity for pharmaceutical search. In each of these contributions, the authors have multiplied an estimate of the probability of discovering a commercially valuable substance by the value of such a discovery. There is considerable disagreement among the studies as to the magnitude of estimation of the latter quantity, although the sober estimates offered by the more recent studies seem the

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[1] We will argue in Section VI that the "marginal species" is in fact a meaningful concept. To anticipate that discussion many biologists--and even many describing apocalyptic scenarios--model the loss of species as a continuous function of the conversion of habitat rather than as a catastroplic discontinuity.

[2] An excellent summary of all these studies may be found in Aylward, 1993.

more probable. The results of these exercises vary widely, ranging from as little as $44 per untested species *in situ* [Aylward, 1993] to as much as $23.7 million (Principe, 1989].[3]

The studies in which the value of indigenous genetic resources in pharmaceutical research have been more thoughtfully derived are useful in that they incorporate detailed treatments of the nature of the benefits to be derived from new Product discovery.We believe the method underlying all these studies to be flawed, however. It is curious that this existing work on economic valuation of genetic resources takes little account of scarcity. Redundant. resources are not scarce, and hence are not of great value on the margin. By multiplying the probability with which an organism sampled at random contains *some* chemical compound of commercial value--whether unique to that organism or not-by the expected value of a successful commercial product earlier researchers have failed to recognize the *possibility* of redundancy among natural compounds.[4] Thus potential values may be overstated in even the more carefully conducted work.

Our approach is more closely related to that of Brown and Goldstein [1984]: we value the marginal species on the basis of its incremental contribution to the probability of making a commercial discovery. Our work is also related to that of Polasky and Solow [1993], Solow, Polasky, and Broadus [1993], and Weitzman [1992, 1993]. In these papers the authors measure biological diversity in terms of the genetic “distances"[5] between related species; in fact, Polasky and Solow [1993], and Weitzman [1992] show how their proposed measures of diversity can be related to the incremental probability of discovering

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[3] There is also some confusion in many of these studies between the average and the margin value of biodiversity. The total value maybe truly astronomical, and hence the average value substantial. We show that the value of the marginal species is likely to be negligible, however.

[4] Note that we emphasize the possibility of redundancy, rather than assert its existence Our findings do not rest on the existence of redundant compounds,but rather on the fact that if the marginal material from which sampling may occur is so rare as not to be redundant the probability of its discovery is small. This point is made more formally below, but should be borne in mind through the entire discussion .

[5] See Weitzman [1992] for an explanation of how distance may be measrured by matching DNA.

commercially valuable compounds. In each of these papers, however, the authors are attempting to describe a *measure* of biodiversity; that is, a ranking by which one collection of organisms may be said to be more or less diverse than another.[6] In our work, we accept current taxonomic[7] practice as the appropriate measure; we suppose that all species within a particular taxon are "equally different." We then ask by how much is *value* augmented by increasing the number of species that maybe tested in new drug research.

Valuation methods based on the work of these other authors will prove more valuable as greater information concerning the genetic constitutions of species-and even individuals-becomes available. Our simpler approach is closer to practical application, however. Biologists estimate there to be between ten and one hundred million living species. Of these, only about 1.4 million have been described [Wilson, 1992] and a far smaller number have been subjected to chemical or genetic analysis [Farnsworth, 1988]. The types of measures suggested by Weitzman and Polasky, Solow, and Broadus simply cannot be performed on a broad scale with existing data and computational limitations. In our work we will treat each new species to be evaluated as an independent Bemoulli trial with an equal probability of yielding the commercial product for which it is being tested. Since much of the literature on biodiversity preservation emphasizes the importance of saving as yet unknown species as genetic insurance against as yet unidentified diseases, our approach seems appropriate.

The reader may find it curious that the roundabout methods we describe for determining values are necessary. One might suppose that our questions could be

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[6] A more recent paper by Polasky and Solow [1994] does deal explicitly, and in a relatively sophisticated manner, with valuation issues. The Polasky and Solow paper does not address values on the margin, however, and it does not incorporate any costs of prospecting--hence, there is no "stopping rule" to determine when additional search is justified. Finally, it would appear that the recent Polasky and Solow paper wee written in part to address omissions in an earlier version of this paper.

[7] We will use "taxonomy," "taxon" and its plural, "taxa" often in this paper. A taxon is a collection of species, or a collection of collections of species, etc.; e. g., a genus, class or order. Taxonomy is the science of categorizing species according to the successfully narrower taxa to which they belong.

answered merely by observing market transactions. We discuss the reasons for which this is not feasible in the next section. Following that, we provide a very brief overview of the natural products pharmaceutical research process. We then turn to a discussion of possible sources of redundancy in genetic prospecting. Our main results are presented in the fourth through sixth sections of the paper. We present a simple model in which discoveries may prove redundant. We are able to derive an upper bound on the value of the marginal species--and, by extension, on the marginal unit of habitat on which it exists. We demonstrate that this upper bound will be substantial only under very optimistic assumptions, and that the value of the marginal species falls off very rapidly if the probability of discovery differs from that which maximizes the marginal value.

Any model that purports to measure something as speculative as the value of a species for its pharmaceutical research potential must be built on a number of simplifying. assumptions. We discuss these assumptions and their implications in a seventh section, but we can summarize hereby saying that we do not believe that a more realistic treatment would change our results much.

We state our conclusions in a final section but we should emphasize one point now. This paper is concerned solely with pharmaceutical reseachers' willingness to pay for indigenous genetic resources as inputs into commercial products. Biodiversity may have important values over and above those as inputs into pharmaceutical research. Our point is not that biodiversity has little value at the margin; it may give rise to a great number of other ecological, moral, and esthetic values that are not captured in market transactions. To the extent that the incipient markets for genetic resources will not generate revenues adequate to support the preservation of endangered habitats, it is all the more important that alternative means for financing conservation be developed.

I. The Value of Genetic Resources in Observed Transactions

One reason for which there is little evidence concerning the prices at which genetic resources have traded is that they are non-rival goods and property rights in them have typically not been well established [see Sedjo, 1992; see also Chichilinsky, 1993; and Vogel, 1993]. The seminal contributions of Coase [1960] and Demsetz [1976; see also Barzel, 1988] suggest that property rights will come to be established either de facto in the form of contracts between parties or *de jure* when the benefits of their definition exceed the costs of their enforcement. The legal and institutional treatment of indigenous genetic resources is, in fact, changing. The Biodiversity Convention [UNEP, 1992] prepared for the 1992 UNCED meetings in Rio de Janeiro and recently signed by the United States guarantees states sovereignty over their genetic resources and forbids their appropriation without prior informed consent. Organizations in many countries are now entering into commercial agreements with foreign pharmaceutical researchers. The most noted of these is probably that signed between Merck and Company, a large U.S. pharmaceutical firm, and Costa Rica's *Instituto Nacional de Biodiversidad* (INBio). This agreement calls for a fixed payment of some one million dollars and premises of substantial royalties in the event of new product discovery [Sittenfeld, 1993].

While institutional developments are indicative of a new enthusiasm and optimism concerning the value of indigenous genetic resources, they provide little evidence concerning the value of unimproved genetic resources *in situ*. "Markets" for transactions in indigenous genetic resources are just beginning to emerge. While payments of between $50 and $200 per kilogram for samples have been reported [Laird, 1993], the interpretation of fixed payments for samples as a measure of the value of resources in situ is suspect for at least two reasons. The first is suggested by our dicussion above: it is not entirely clear that the collector has (or should have) legal title to the samples she sells. For this reason, observed "prices" might be misleadingly low. The second reason is that sample collection is typically a much more difficult process than it may appear at first. Payments made for samples may reflect compensation for collection and processing labor and taxonomic expertise rather than rents for the materials themselves.[8]

Compensation for access to samples is often not made in the form of simple cash transactions, however. Many agreements specify royalty provisions rather than up-front payments. Inasmuch as the terms of these provisions are generally secret, and the parties' estimation of both the probability of discovery and the payoff in the event that a valuable discovery is made are unknown, little can be inferred about the value of resources in situ from public information concerning these contracts. For these reasons, most existing attempts to estimate the value of indigenous genetic resources for pharmaceutical research have been based on inferences from indicators other than observed transactions.

II. The Use of Indigenous Genetic Resources in Pharmaceutical Research

Indigenous genetic resources are the genetic codes containing the "recipes" for chemical compounds of potential value m pharmaceutical products. These recipes can be exploited for commercial purposes by acquiring a breeding stock of the organism that produces the desired compound transplanting genes, or using the naturally occurring compound as a model for the synthesis of the same or related compounds. Pharmaceutical research on natural products is more often intended to develop "leads" than to identify natural products that can be used in an essentially unmodified form. Leads are promising molecules: blueprints of compounds that may show promise in their naturally occurring form, but must be modified to increase efficacy or reduce side-effects.

Part of the reason for the increased recent interest in natural products research is a renewed appreciation of the importance of natural leads. While considerable efforts at "rational design" of drugs from inorganic materials continue, researchers have also come

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[8] The Merck-INBio agreement illustrates this point. Of the million-dolloar up-front payment, less than ten percent was designated for conservation activities. The remainder went for equipment purchases and to defray INBio's expenses [Sittenfeld and Gamez 1993].

to recognize that nature has perfected chemicals that synthetic chemists might never dream up [Reid et al., 1993]. Wild plants and animals have evolved elaborate chemical means to enhance reproductive success, deter predators, and resist infection. These chemicals may have great promise in pharmaceutical applications.

The development of new drugs from indigenous genetic resources proceeds in many steps and may take ten or more years from the time a promising lead is discovered to the first commercial sales of derived compounds. The process begins with field collection. It is important that collection be undertaken by trained taxonomists; appearance and location must be carefully recorded so that finds will be replicable. Samples are next dried and ground. While these processes may sound straightforward, they must also be performed to tight tolerances. The next step is typically to extract active compounds with a chemical solvent. Extracts are then tested to determine activity for certain purposes. These tests, or assays, are today typically performed *in vitro* in a matter of minutes, and are intended to determine if a certain chemical reaction occurs.

Once products with promising properties are identified, their active compounds must be isolated. These isolated active compounds may then be “optimized” that is, chemically modified to increase efficacy or reduce side-effects. Experimental drugs are subjected to several rounds of clinical trials, which may, of course, be terminated at any point if it is determined that the research is unlikely to be successful. Production planning, patent application, and pursuit of regulatory approval maybe conducted concurrently with other activities. Finally, if tests have beta successful and regulatory hurdles cleared, commercial sales may begin.

III. Value and Redundancy in Indigenous Genetic Resources

In this paper we seek to determine the value of indigenous genetic resources in situ for pharmaceutical research, and, by extension, the incentives that might be created by pharmaceutical research for the preservation of undisturbed habitat; we derive a demand curve for indigenous genetic resources and their habitat. We then determine from this demand curve the willingness to pay for the “marginal species."[9]

In deriving this demand curve we must consider not only the likelihood that useful products will be found in one sample, but that they will be duplicated by other finds. The marginal value of genetic information for medicinal purposes is measured by its contribution to the improvement of available health care. For example, the value of a new cancer treatment is determined by its capacity to improve remission rates, reduce side effects, lower costs, and so forth. A new drug that maybe effective but is identical or inferior to an existing treatment is of little value. While the discovery of a novel compound may not often prove completely superfluous it is often the case that one product will largely duplicate another, or that discovery of one effective compound will reduce the urgency, or even eliminate the need to continue research on others.[10]

The essence of the argument we will make more formally below is that *regardless* of the probability with which the discovery of a commercially useful compound may be made, if the set of organisms that may be sampled is large, the value of the marginal species may be very small. At any given time, researchers will be searching for compounds effective in particular application. If the probability that a species chosen at random will yield an effective compound is high, the probability that two or more species

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[9] We will, for want of a better index, treat "species" as the basic units of genetic differentiation. It would be inaccurate to suppose that the all species are seperated by the same degree of genetic variation. It is common, however, to consider the species both as the basic unit of biological diversity [Wilson, 1992] and of economic value.

[10] This point is illustrated by taxol, a drug derived from the bark of the pacific yew tree that is used to combat ovarian cancer. Though perhaps the most important anti-cancer find in recent years, the drug provides only an incremental improvement in our ability to treat the disease. Comparing it to the most effective alternative treatment, while taxol has in some tests shrunken tumors in a higher proportion of women for a few more months, is has more severe side effects, costs three times as much, and has not conclusively extended lives. “The Aura of Miracle Fades from a Cancer Drug,” Gina Kolata, *New York Times*, November 7, 1993.

will be found to do so is also high. To the extent that additional species from which to sample are likely to be redundant, their marginal value will be low. Conversely, if potentially valuable compounds are so rare as to make their discovery in two or more species highly unlikely, the probability of their discovery in any species will be unlikely.

We will treat these issues more formally below; we note in passing, however, that there are several reasons for which redundancy of genetic resources may be relatively common. First, individuals of the same species maybe redundant. The same species may be found over a wide range. If all representatives of a species produce a particular compound, individuals in excess of the number needed to maintain a viable population are redundant. Second, there are numerous instances in which identical drugs, or drugs with similar clinical properties, have been isolated from different species [Farmsworth, 1988].[11] To give a recent example, the discovery of the anti—cancer drug taxol m the Pacific Yew of Western North America has set pharmaceutical researchers looking for similar compounds in its old-world relatives.[12] Given the numerous examples of parallel morphological development in the evolution literature, it should not be surprising to find that different organisms that have evolved in similar ecological nicks have developed similar chemicals.

Finally, there is a dimension of what we might label clinical or medicinal, redundancy. Very different compounds, perhaps even drugs working through different mechanisms, may be effective in treating the same set of symptoms. Moreover, while the inventiveness of nature in developing useful compounds is much extolled as a factor in the increased demand for natural products for pharmacological research [Findeison and Laird, 1991], it is possible that synthesis from non-organic sources would yield substitutes for natural product leads.

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[11] It may also be the case that there are a host of other sources of common compounds that remain undiscovered because current sources are adequate.

[12] See, e. g., “A New Cancer Drug May Extend Lives - at Cost of Rare Treees,” Marilyn Chase, *Wall Street Journal,* April 9,1991.

IV. A Simple Model

In this section we derive a simplified demand function for indigenous genetic resources in pharmaceutical prospecting, determine the maximum willingness to pay for the "marginal species," and consider the sensitivity of the value of the marginal species to the probability of discovery and assumptions concerning overall profitability. We begin with a very simple model. Suppose that medical researchers have identified a need for a new product. A new product, if successfully developed, will earn net revenues of *R*. *R* is assumed to be net of production, advertising, and marketing costs, but gross of any costs of product research and development (i. e., costs of determining whether or not a natural material will in fact lead to a commercially successful product). These costs of research and development will be denoted by *c*.

Suppose that there are n species of organisms that may be sampled in the search for the new product. Suppose further that p is the probability with which any species sampled at random yields a successful commercial product. We treat each new sampling as an independent Bernoulli trial with equal probability of success. Testing for a particular application ends with the first success: once a successful product is found, further discoveries would be redundant. Thus, the value of the entire collection of n samples is

$$\begin{aligned} V(n) &= pR - c + (1-p)[pR - c] + (1-p)^2[pR - c] + \ \ldots \ + (1-p)^{n-1}[pR - c] \\ &= \frac{pR - c}{p}\left[1 - (1-p)^n\right]. \qquad (1) \end{aligned}$$

That is, with probability p, the first organism tested yields a commercially successful product and the search ends. With probability 1-*p,* the first organism tested does not yield a successful product and the second organism is tested, and so on. If none of the *n* organisms tested yields a commercially successful product, search ceases.

What is the value of the "marginal species?" In other words, how much does total expected value increase with the addition--or decrease with the loss--of a species that could be tested? The increase in total value to be realized by the preservation of an additional species is

$$V(n+1) - V(n) = \frac{pR-c}{p}\left[1-(1-p)^{n+1}\right] - \frac{pR-c}{p}\left[1-(1-p)^{n}\right]$$

$$= (pR-c)(1-p)^{n} \qquad (2)$$

we will abbreviate this expression for the value of marginal species as *v(n)* in what follows. Note the straightforward intuition underlying expression (2): the value of the marginal species is the expected payoff in the event it is sampled $pR - c$, times the probability with which search is unsuccessful in the set of n other species, $(1 - p)^n$.

Obviously, the buyer must believe that $pR-c > 0$ if any sampling is deemed worthwhile; on the other hand, as p becomes larger the magnitude of $(1-p)^n$ declines more quickly than than of $pR - c$ increases. In what follows, we describe how the value of the marginal species varies with the probability of success m any given trial. We derive two main results in this section. First, one must make optimistic assumptions in order to believe that the value of the marginal species is very large even if the probability of success in each trial were that which maximizes the value of the marginal species. Second, the function relating the value of the marginal species to the probability of success in any given trial is sharply peaked. With large numbers of organisms from which to sample, not only is the maximum value of the marginal species low, but the value also falls off steeply if the probability of success differs even slightly from the maximizing probability.

Differentiate (2) with respect to p to find that

$$\frac{\partial v}{\partial p} = -n(pR - c)(1-p)^{n-1} + R(1-p)^{n}$$

$$= [R - c - (n+1)(pR-c)](1-p)^{n-1} = 0 \qquad (3)$$

when p is chosen to maximize *v(n)*.

The second-order condition for a maximum requires that

$$\frac{\partial^2 v}{\partial p^2} = -(n-1)\left[R - c - (n+1)(pR-c)\right](1-p)^{n-2} - (n+1)R(1-p)^{n-1} \leq 0.$$

As the satisfaction of the first-order condition requires that the expression in square brackets is zero at the maximum the second-order condition is satisfied. It is also easy to see that there is only one extreme point on the interval [0, 1], so the probability that maximizes the value of the marginal species is unique.

The first-order condition may now be expressed as

$$p^*R - c = \frac{R-c}{n+1},$$

or

$$p^* = \frac{R + nc}{(n+1)R} = \frac{1}{n+1} + \frac{n}{n+1}\frac{c}{R} \qquad (4)$$

The restrictions that $p^*R - c > 0$ and $p^* < 1$ are both satisfied if $R > c$.[13]

Using (4), we can derive the maximum possible value of v, which we will call v*:

$$v^* = v(n)\Big|_{p^*} = \frac{R-c}{n+1}\left(\frac{R-c}{R}\frac{n}{n+1}\right)^n. \qquad (5)$$

The approximation $\left(\frac{n}{n+1}\right)^n \approx \frac{1}{e}$ (where e is the base of the natural logarithm, approximately 2.718) is very accurate for values of n on the order of those we are considering for wild species. Incorporating this approximation, we have

$$v^* \approx \frac{R-c}{(n+1)e}\left(\frac{R-c}{R}\right)^n. \qquad (6)$$

Expression (6) still involves a number of variables concerning whose magnitudes and relative magnitudes we have not yet said anything. At this point we can see, however, that it is entirely possible that the *maximum* possible value of the marginal species could be insubstantial. As n grows large, v^* will be small for even relatively small values of c. This is true for two reasons. The first is the $n + 1$ in the denominator of (6). The second

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[13] Of course, we would expect $R >> c$; the value of a proves discovery substantially exceeds the cost of evaluation.

is that $\frac{R-c}{R}$ is raised to the nth power in (6); for large values of n, this expression will become quite small for even moderate values of c relative to R.

It is also revealing to express (6) in another way. From (1), we can define the expected revenues of a program searching for a particular product as $\Pi = R\left[1-(1-p)^n\right]$, and the total expected costs as K = $\frac{c}{p}\left[1-(1-p)^n\right]$. We can then rewrite

$$\frac{R-c}{R} = 1 - \frac{pK}{\Pi}.$$

Using (4) to evaluate this expression at p*, we find

$$\left(\frac{R-c}{R}\right)^n = \left(\frac{(n+1)(\Pi-K)}{(n+1)\Pi - nK}\right)^n$$

For large n, we have approximately

$$\left(\frac{R-c}{R}\right)^n \approx e^{\frac{-K}{\Pi-K}}$$

and the maximum value of the marginal species is approximately

$$v^*(n) \approx \frac{R-c}{(n+1)} e^{\frac{-\Pi}{\Pi-K}} \qquad (7)$$

AS K approaches II, *v*(n)* again approaches zero. In short, the value of the marginal species can only be high if the expected aggregate profitability of the research venture is high. In Figure 1 we illustrate this **relationship.**[14]

It also bears mentioning both that the marginal species takes on its maximum value at a probability relatively close to that at which prospecting "breaks even" and that the value of the marginal species declines relatively rapidly with respect to probability after having reached a maximum. Recall that prospecting is only profitable in expectation if

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[14] The curve in Figure 1 quickly approaches a linear relationship; recall from (7) that

$$v^*(n) = \frac{R-c}{(n+1)} e^{\frac{-\Pi}{\Pi-K}}.$$

For R>>K, the exponential term is almost constant, so the linear term in R - c dominates.

$pR - c > 0$, i. e., $p > R/c$. Our statements about relative closeness maybe made more concise if we define a basic unit

$$\mu = p^* - \frac{R}{c} = \frac{1}{n+1}\frac{R-c}{R}. \tag{8}$$

Note that μ is necessarily less than $\frac{1}{n+1}$.

If we now consider v, the value of the marginal species, as a function of p, the probability of success in any given trial (fixing n), it follows that $v(p^* - \mu) = 0$. More generally,

$$v(p^* + m\mu) = (m+1)\frac{R-c}{n+1}\left(\frac{n-m}{n+1}\frac{R-c}{R}\right)^n.$$

For large n, the approximation

$$v(p^* + m\mu) \approx \frac{R-c}{n+1}\frac{m+1}{e^{m+1}}\left(\frac{R-c}{R}\right)^n$$

is very accurate. Thus, to a very close approximation

$$v(p^* + m\mu) \approx \frac{m+1}{e^m}v(p^*). \tag{9}$$

The shape of this function is illustrated in Figure 2; it is, of course, the same as the graph of $(pR-c)(1-p)^n$. Note the extreme concentration at the function's peak. Recall that $< \frac{1}{n+1}$; thus, on an interval of length less than $\frac{10}{n+1}$, $v(n)$ varies from 0 to its maximum value to $10e^{-9}$ = 0.0012 times its maximum value. p* itself is greater than $\frac{1}{n+1}$. If, as seems likely, a researcher cannot predict the probability with which she anticipates success in any given sample evaluation within an order of magnitude *ex ante,* her expectation of the value of the marginal species is likely to be very low.

V. Some Specific Examples

It is impossible to estimate the value of marginal species with any precision. Even deriving an estimate for its maximum possible value is a highly speculative exercise. We can, however, get some idea as to the magnitudes involved by using some data from the pharmaceutical industry. While our estimates are little more than back-of-the-envelope calculations, a more careful treatment might well yield still lower numbers.

In order to relate our model to real-world data, we must aggregate over all possible discoveries. Some of what we believe to be the excessive enthusiasm for the potential of genetic prospecting as a conservation strategy stems from an unrealistic view of the number of products" to be generated from prospecting activities.[15] One rarely finds things for which one does not look. Genetic prospectors subject samples to a limited series of tests at any given time. While the history of science records many serendipitous discoveries, they are the exceptions. It would be difficult to come up with a figure for the number of applications for which species are tested,[16] whatever that number, however, we do have statistics on the numbers of new products developed. We should require as a reality check that the probability of discovery times the number of applications for which tests are performed not vastly exceed current numbers of new products developed.[17]

We will suppose that there exist a series of "potential products" that might be derived from genetic resources. Potential products might be regarded as cures for diseases. The demand for them may arise as new infectious diseases become widespread,[18] as demographic characteristics change and the health needs of certain groups become more important,[19] or as new technologies are developed.[20] We label these

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[15] We do not treat agricultural and industrial applications here. Casual empiricism and conversations with researchers suggest that the value of the marginal species for these purposes may be much lower still, as a still greater number of substitute research opportunities may be available (in agricultural research, for example, pest-resistant strains can often be developed from the large number of very close--often of the same species--relatives of cultivated varieties).

[16] Conversations with researchers suggest that on the order of one hundred tests or less are done on species for their pharmaceutical potential.

[17] If more thorough genetic prospecting activities did in fact yield a deluge of new products we would have to wonder again if the marginal new product were of any appreciable value.

[18] For example, the AIDS virus was not identified until the 1980s.

[19] The aging of the population and the increased need for geriatric care are good examples here.

as potential products, as there is no assurance that solutions to newly identified needs can actually be found. It is not unreasonable to suppose that new potential products are generated by a Poisson process with **parameter** λ. Then, in expectation, λ potential new products will be identified every year. We will suppose that λ remains constant overtime: potential new products are identified at a more-or-less constant rate.

We might suppose that each new potential product *j* identified at time *t* would have a stream of revenues net of research and development costs denoted by R_{jt}. Similarly, we could say that the cost of evaluating the potential of the ith species for its use in deriving the *j*th potential product at time t is a random variable c_{ijt}. It is not unreasonable to assume, at this level of detail, that all the *R's* and *c's* are statistically independent and denote the expectation of each as *R* and *c*, respectively. If future returns are discounted at a constant rate r, the expected value of the marginal species is simply

$$\sum_{t=0}^{\infty} \lambda(1+r)^{t}(pR - c)(1-p)^{n} = \frac{\lambda}{r}(pR - c)(1-p)^{n}. \qquad (10)$$

As was noted above, if we are considering extremely large numbers of species, the value of any one species must be negligible. While biologists are unable to specify the number of living species to within even an order of magnitude, a reasonable lower bound would be ten million specks. *The "base case" estimate we report below would have been reduced by forty-one orders magnitudes if we had assumed that all of ten million species were equally likely to yield a successful product.*

Let us, therefore, narrow the range of species over which we consider searching. Some have argued that phytochemicals-compounds produced by higher plants--have exceptional pharmaceutical potential [see, e. g., Joffe and Thomas 1989]. These compounds may be unlikely to be produced by other types of organisms, and may have substantial pharmaceutical value. Aspirin, quinine, and the anti-cancer drugs vincristine,

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[20] For example, the demand for immunosuppresant drugs has increased greatly as a result of the progress that has been made in organ transplant surgery.

vinblastine, and taxol are all derived from higher plants. There are estimated to be at least 250,000 living species of higher plants [Myers, 1988; Wilson, 1992].[21]

We will consider the value of the marginal species of higher plant assuming that p is chosen so as to maximize that value. Regrettably, there are no reliable estimates of the parameters λ, R, or c each might be inferred indirectly from knowledge of aggregate industry success rates, revenues, and costs, however. We will ask what the values of the parameters we seek would be if observed data were generated by the probability of success that maximizes the value of the marginal species.

Between 1981 and 1993 the U. S. Food and Drug Administration approved an average of 23.8 new drugs per year [PMA, 1982-1994]. This rate was relatively stable (see Table 1), varying between 14 in 1983 and 30 in 1985 and 1991. There is no discernible trend in the data. As new drug applications include both compounds first approved in the U.S. and subsequently sold to the rest of the world, as well as drugs already sold elsewhere but just being approved in the U. S., we take these figures to be representative of world discovery rates.

About one third of all prescription drugs are derived from higher plants [Chichilnisky, 1993]; we will assume that ten new drugs per year are expected to be discovered from investigating higher plants. The expected number of new products developed per year is the expected number of new potential products identified, λ, times the probability with which a successful commercial product is developed, $1-(1-p)^n$.

Di Masi, et al. [1991] estimate pharmaceutical research and development expenditures per successfully derived product to be $231 million. A recent report suggests that “a reasonable upper bound” on the figure is $359 million [OTA 1993]. We

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[21] Farmsworth [1988] places the number at between 250,000 and 750,000, so our estimates of the value of the marginal species should again be biased upward.

will assume a value of $300 million for our calculations. In our notation the R&D cost per successful product developed would be expressed as $\frac{c}{p} = \frac{K}{1-(1-p)^n}$.

We summarize some data relating net revenues to R&D costs for major pharmaceutical companies in Table 2. We assume that marketing and administrative costs vary in proportion to the number of products marketed, so we define net revenues as sales less production costs and marketing and administrative costs.

This data cannot be applied directly, however. In our model we have assumed that samples arc evaluated, costs are incurred, and revenues received instantaneously. In the real world of course, these things occur overtime. Let us consider, then, a pharmaceutical company that earns a stream of revenues from products of various vintages. For simplicity, suppose that products differ only by their dates of discovery; each product of the same age earns the same net revenues (in expectation) regardless of when it reaches that age. $\lambda[1 - (1-p)^n]$ is the number of products expected to be developed in any given period and let ϕ_t be the expected net revenue received by a product of age *t*. Then the total expected net revenues of a firm of age T will be

$$\Phi = \lambda\left[1-(1-p)^n\right]\sum_{t=0}^{T}\phi_t .$$

If we assume that net revenues of older products eventually decay and the firm is sufficiently old, the firm's total expected net revenues should be constant over time under our assumptions.

The expected present value of the net revenues of products developed in period T will be less than the value of its current receipts, however, as these revenues will not be received immediately. That is,

$$\lambda\left[1-(1-p)^n\right]R = \lambda\left[1-(1-p)^n\right]\sum_{t=0}^{T}\frac{\phi_t}{(1+r)^t}.$$

A reasonable specification of the ϕ_t's might be to suppose a stylized model of patent protection. Suppose that new products are the exclusive property of their inventors for T periods, during which constant expected net revenues of ϕ are received. After the expiration of the patent we will suppose that all profits are competed away. Under these assumptions we would find that

$$R = \frac{1-(1-r)^{T}}{rT}\phi.$$

It is clear that $\frac{1-(1-r)^{T}}{rT}$ is less than one. To give some idea of general magnitudes, if r = 0.10 and T = 17--values that might be assumed in consideration of pharmaceutical company discount rates and patent law in the U.S.--$\frac{1-(1-r)^{T}}{rT}$ would be about 0.49.

We might also do a similar correction for the timing of research expenditures; even in a steady state, a firm's current R&D expenditures overstate the expected present value of its expenditures on products under development, as the latter will be incurred in the future, and hence, discounted. The most favorable assumption that we could make on costs would be that they are all incurred at the last possible moment, however. All R&D costs are, by definition, incurred before a product is marketed, so revenues are not received until all costs are incurred. Thus, if we discounted from the time at which research begins until costs are incurred, we would also want to discount from the time at which research begins until revenues begin to be received. These would be offsetting corrections, however (we care about the ratio of total expected costs to total expected revenues).

Combining all these considerations it seems generous to suppose that an investment in pharmaceutical R&D pays a fifty percent return. If the cost per successful product developed is $300 million, then, we will suppose that the net revenue is R = $450 million. Finally, we will suppose that pharmaceutical firms discount future returns at ten percent per year.

The results of an exercise based on expression (6) and these assumptions are summarized in Table 3. Our assumptions imply that the probability of hitting on any given species for any given potential product that maximizes the value of the marginal species would be about twelve in a million. Over an entire collection of 250,000 species from which to sample the probability of making a hit is slightly over ninety-five percent. The expected cost of evaluating a sample is around \$3,600. The maximum possible value of the marginal species is slightly less than \$10,000.

We must emphasize that these estimates are extremely sensitive to changes in assumptions, however. Recall that we have evaluated the marginal species at that probability of success that maximizes its value. The results reported in Table 3 indicate that $p^*= 0.000012$. If we continue to assume that $c = \$3600$ and $R = \$450,000,000$, but allow p to vary, we may get very different results. We must have $p \geq 0.000008$ in order to have the expected value of conducting any test be positive. From that level, however, the value of the marginal species quickly increases to the peak at \$9,431. If p were to increase further, to 0.000040, the value of the marginal species declines to only about \$67. If p were an order of magnitude greater than p^*--but still only on the order of 10^{-4}--the value of the marginal species would plummet to less than \$0.0000005!

The second assumption that can make a great deal of difference in our results concerns the relative magnitude of net revenues and costs. In our base case scenario we assumed that expected net revenues exceed expected research costs per successful new product derived by fifty percent. If we assumed instead that expected net revenues exceed expected costs per successful product by twenty-five percent, the value of the marginal species would be only \$1,017.53; if expected net revenues exceed expected costs per successful product by ten percent the value of the marginal species would be \$2.20.[22]

We will seem the next section that even numbers on the magnitude of \$10,000 may translate into very limited incentives for the preservation of threatened habitats. It is

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[22] Of come, if we assumed that net revenues exceed expected costs per product developed by a wider margin, we would obtain greater values for the marginal species. At a certain point however, these results become implausible for other reasons; we should not expect the overall profitability of the industry to reach unlikely levels.

worth emphasizing again, however, that we have generated values of that magnitude only under what we regard as generous assumptions. We do not claim to have proved that the marginal species is necessarily of negligible value; extremely fortuitous circumstances may combine to create greater values. Our results do suggest, however, that only very optimistic researchers might demonstrate a substantial willingness to pay.

VI. Incentives for the Conservation of Endangered Habitat

We have concentrated to this point on efforts to evaluate the worth of the "marginal species." We are, perhaps, past due in Mining this concept and justifying its importance. Economists should be familiar with the notion of valuing resources on the margin but maybe uncomfortable with applying marginal analysis man ecological context. How can one identify the marginal element of a large and complex ecosystem? We will elaborate on our assumptions in this context in a moment; it suffices to say for now that we will assume that the number of species in an ecosystem declines as a continuous function of habitat loss.

It is important to note, however, that we are addressing explicitly only questions concerning the value of the marginal hectare of land on which the marginal species grows. That is, we are concerned only with matters of land conversion. Other human impacts may be more widely felt. The introduction of exotic species, the release of pervasive pollutant, or the effects of global climate change may have devastating impacts on biological diversity. A marginal analysis maybe inappropriate for the consideration of such phenomena. In the event of apocalyptic ecosystem collapse, however, the lost potential for pharmaceutical research might well be the least important of our worries.

Much of the current concern with respect to the extinction of species arises from the destruction of habitat. There is an extensive literature on the relationship between habitat area and the richness of species. We will employ a widely used model in the ecological literature, advanced by Preston [1960; 1962] and incorporated by McArthur and Wilson [1967] in their influential theory of island biogeography. While this model has been widely criticized by ecologists [See for example, Simberloff and Abele, 1982; Boeklen and Gotelli, 1984; and Zimmerman and Bierregaard, 1986] for its inability to predict the viability of individual populations and its resultant lack of utility in refuge design, its predictions are likely to bias the estimate of the value of the marginal hectare upward,[23] and for this reason we will employ it. We might also note in passing that it is generally species-areas relationships that are employed to generate even the more apocalyptic estimates of impending biodiversity losses.

The theory of island biogeography predicts that the number of species, n_i, in a particular taxon found in an area of size A_i is given by

$$n_i = \alpha_i A_i^Z, \qquad (11)$$

where α_i is a constant that measures the species richness potential of an area and Z a constant whose value is approximately 0.25 [see e.g., McArthur and Wilson, 1967; Preston, 1962; Wilson, 1988].

To infer the maximum possible value for the marginal hectare of land for genetic prospecting, then, we can differentiate V[n(A)] with respect to A to find that

$$\frac{\partial V}{\partial A} = \frac{\partial V}{\partial n}\frac{\partial n}{\partial A}.$$

$\partial n_i/\partial A_i$ can be found by differentiating (11) with respect to A:

$$\frac{\partial n}{\partial A} = Z\alpha_i A_i^{Z-1} = Z\frac{\alpha_i A_i^Z}{A_i} = ZD_i, \qquad (12)$$

where D_i is the species density, i.e., the number of species per unit area.

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[23] Island biogeography, as the name suggests, is based on the distribution of species in physically isolated habitats--islands in mid-ocean, labs in large land masses, isolated mountaintops, and the like. The degree to which habitat conversion by, for example, felling forests for agriculture, actually isolates populations is much disputed [ace, for example, Lugo, Parrotta and Brown, 1993].

We can combine expression (12) with our earlier results presented in Table 3 to estimate the conservation incentives that would arise in particular threatened habitats. If we accept the figure of $9,431 for the value of the marginal species of higher plant, we can translate this number into a figure for a pharmaceutical company's maximum willingness to pay to conserve a marginal hectare. In Table 4 we have entered data on Norman Myers's [1988; 1990] eighteen biodiversity "hot spots." We find that the greatest willingness to pay might be on the order of $20 per hectare in Western Ecuador. In other areas with less genetic diversity the willingness to pay would be considerably lower, on the order of a dollar per hectare or less. Again, it should be emphasized that even these very low estimates arise under optimistic assumptions concerning the probability of discovery and expectations of profitability. Equally plausible conjectures concerning these parameters would yield radically lower values.

VII. Caveats and Extensions

The simple model we have developed above and on which we based the numerical exercises we have reported is unrealistic in several respects. In this section we consider two ways in which it might be improved and how our findings might differ if a more realistic-if less tractable-model had been specified. We then discuss how other sources of uncertainty might affect our results. We conclude this section with some reasons for which we believe the model presented in Section III nevertheless provides useful insights.

Sequential Testing

In the simple model specified above we treat the cost of testing each individual species as a random variable drawn independently from the same distribution. In the real world, of course, testing is a complicated and extensive process. The first test may be very simple (e.g., the "test" may consist of determining whether or not a given species belongs to a taxon considered likely to contain the desired compound), the next test somewhat more complicated and expensive, and so forth.

Consider a simple example. Suppose that two tests are required to determine if a sample contains the desired product. Suppose that the (expected) cost of the first test is c_1 and that of the second c_2. Denote by p_1 the probability that a sample chosen at random "passes" the first test and by p_2 the probability that it "passes" the second. As before, let R be the (expected) net revenues earned by a successful product--i.e., one that passes both tests. Then the value of the marginal sample is the expected value of evaluating a sample at random, net of expected testing coats, times the probability with which no successful product is identified among the first n species sampled. That is,

$$v(n) = \left[p_1 p_2 R - (c_1 + p_1 c_2)\right]\left[1 - (1 - p_1 p_2)^n\right].$$

Differentiating with respect to both p_1 and p_2 yields two first-order conditions:

$$\left[p_1 p_2 R - (c_1 + p_1 c_2)\right] n p_2 (1 - p_1 p_2)^{n-1} + (p_2 R - c_2)\left[1 - (1 - p_1 p_2)^n\right] = 0$$

and

$$\left[p_1 p_2 R - (c_1 + p_1 c_2)\right] n p_1 (1 - p_1 p_2)^{n-1} + p_1 R\left[1 - (1 - p_1 p_2)^n\right] = 0$$

Suppose that both of these conditions hold. Multiply the first by p_2 and the second by p_1. As both expressions are equal to zero, we must then have

$$(p_1 p_2 R - p_1 c_2)\left[1 - (1 - p_1 p_2)^n\right] = p_1 p_2 R\left[1 - (1 - p_1 p_2)^n\right], \text{ or}$$

$$p_1 c_2 = 0.$$

Obviously, p_1 cannot be zero if the species is to have any value. If c_2 were zero we would have the problem we have already solved above, with p replaced by $p_1 p_2$ and no meaningful basis for regarding the probability as being separate. Thus, for $c_2 > 0$ we conclude that the value of the marginal species is maximized if $p_1 = 1$; that is, the assumption that the first-order conditions are simultaneously satisfied is contradicted It is easy to demonstrate that this result generalizes to any finite number of required sequential tests. We conclude, then that the assumption that all sequential tests are compressed into a single number denoting the expected cost of all testing does not bias our estimate of the value of the marginal species downward.

Continued Search

Another way in which our simple model has not been realistic is in its treatment of search following initial sampling successes. We have assumed that search stops after the first success. As we have noted above, however, practice differs from this abstraction. The identification of compounds of potential value in one species may lead to a continued search for similar but more effective compounds in others. Let us consider how this consideration might be incorporated in a more realistic model, what might be gained in detail, and what might be lost in tractability.

A more realistic treatment might specify the payoff to a particular sample taken at random as a random variable θ. Assume again that the cost of evaluating a sample--of determining the realization of θ--is c. We can generalize the model we have presented above by noting that, under reasonable distributional assumptions, once a realization of θ in excess of some certain value, call it θ^*, is encountered search will cease. That is, let $f(\theta)$ be the distribution of θ and $(0, \bar{\theta})$ its support (it is convenient-and realistic--to set the lower bound of the support of θ equal to zero: the pharmaceutical researcher cannot be obliged to develop products of negative value). Suppose also that the θ's are independently and identically distributed across species.

The expected gain to be realized from evaluating an additional sample given that one of value x has already been identified is

$$\int_x^{\bar{\theta}} (\theta - x) f(\theta) d\theta \; - \; c. \tag{13}$$

Denote by θ^* that value of *x* for which (13) is exactly zero.[24]

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[24] Obviously, such a θ^* will exist if $\bar{\theta}$ is finite. More generally, we must require that there not be too much mass in the right tail of the distribution of θ. It seems entirely reasonable to suppose that such a θ^* exists in our context.

Suppose that $\tilde{\theta}(n)$ is the greatest value of θ encountered in a collection of size n (i. e., $\tilde{\theta}(n)$ is the greatest order statistic in a collection of size n). Now we cart denote the expected value of a collection of *n* species with respect to a particular potential product as

$$V(n) = \left([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c\right) + F(\theta^*)\left([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c\right) + F(\theta^*)^2\left([1-F(\theta^*)]E(\theta|\theta \geq \theta^*)-c\right) + \ldots + F(\theta^*)^{n-1}\left([1-F(\theta^*)]E(\theta|\theta \geq \theta^*)-c\right) + F(\theta^*)^n E\left(\tilde{\theta}(n)|\, \tilde{\theta}(n) < \theta^*\right). \qquad (14)$$

This expression is relatively straightforward--and similar to (1). Its mth (m $\leq$ *n)* term consists of the probability with which the mth species yields a product so successful as to obviate the need for further search, times the expected value of the product given that it is sufficiently valuable that search is suspended less the cost of sample evaluation, all times the probability that a product so successful as to motivate the suspension of search is not discovered m the previous *m* - 1 species sampled. The final term is the product of the probability that no species sampled yields a product sufficiently valuable as to motivate the end of search and the expected value of the most valuable product found in searching over all n species, conditional on none yielding a value greater than θ^*.

Note that

$$F(\theta^*)^n E\left(\tilde{\theta}(n)|\, \tilde{\theta}(n) < \theta^*\right) = \int_0^{\theta^*} \theta n f(\theta)F(\theta)^{n-1}d\theta,$$

as $nf(\theta)F(\theta)^{n-1}$ is the probability density of the greatest order statistic in a sample of size *n*. It is now straightforward to show that

$$\begin{aligned} v(n) = V(n+1) - V(n) &= \left([1 - F(\theta^*)]E(\theta|\theta \geq \theta^*) - c\right)F(\theta^*)^n \\ &\quad + \int_0^{\theta^*} \theta f(\theta)F(\theta)^{n-1}\left[(n+1)F(\theta) - n\right]d\theta. \end{aligned} \qquad (15)$$

The term on the first line to the right of the equal sign is familiar from (2); it is (2), with *p* replaced by 1- $F(\theta^*)$ and R replaced with $E(\theta|\theta \geq \theta^*)$. It is obvious that (2) and (15) coincide when the distribution of θ is sharply bimodal: if all “failures" are without commercial value and the value of all “successes” are tightly clustered.

The question is, then, whether the value of successes are clustered. We believe that they are likely to be. Continued search for pharmaceutically active compounds for a particular purpose after one “successful” compound has been discovered is likely to be geared toward finding other species in which the same or similar compounds are produced more plentifully. In other words, continued search may be undertaken in order to lower costs of production. Production costs are a relatively unimportant component of pharmaceutical industry profits. Thus, large increments in value maybe unlikely to result from subsequent discoveries.

Moreover, it must be remembered that we are asking what the expected value of an untested species is at the margin and *ex ante*. Some additional testing maybe done because *conditional* expectations of value are high enough to justify it. While variations in chemical properties among related species may motivate continued search, the lion’s share of the value may be realized by finding an organism that serves to identify the taxon to be the subject of further search. All organisms in the taxon may be fairly close substitutes for this purpose. All organisms not in the identified taxon have a conditional value of zero.

Two Additional Sources of Uncertainty

While we have mentioned that R and c my be regarded as the expectations of random variables, we have not dealt explicitly with* underlying stochastic expressions. If we replace each by the corresponding random variable, it can be shown that the maximum value of the marginal species in our simple model--expression (6)--is convex in both. If we sum overall anticipated future potential products and evaluate the resulting expression at the expectations of R and c, our estimate of the maximum possible marginal value will be biased downward. This consideration does not greatly concern us, however. As shown in figure 1, and explained in footnote 14, expression (6) is nearly linear when profit margins are appreciable. The function is sharply curved only when marginal values are negligible anyway.

Another source of unmodeled uncertainty may be more problematic. The extinction of a species is the example *par excellence* of an irreversible (dis-)investment.[25] It is well known [see, e. g., Pindyck 1991] that such investments should be made only when their expected benefits exceed their costs by a positive differential. The size of this differential is determined by the parameters of the stochastic process by which benefits (and, in a fuller treatment, costs) are assumed to be generated. In particular, greater uncertainty in the process induces a greater differential. This "option value" argument is also often emphasized in the ecological and environmental literature on the value of endangered resources for pharmaceutical research.

We do not propose to suggest a figure by which our earlier numerical examples might be inflated in order to correct for this uncertainty. We will suggest, however, that overall uncertainty may not be great. It is true that spectacular new medical needs are identified from time to time. The sum of marginal values with respect to the various potential products for which testing may take place might evolve considerably more smoothly, however.

Other Extensions

We have just noted two ways in which our treatment of uncertainty may result in estimates of the maximum possible value of the marginal species that are too low. It is also likely that the sharply peaked shape of the value of the marginal species that are too low. It is of the probability with which any species sampled at random yields a "hit" is an artifact of our assumption that all "hits" are equivalent--although, inasmuch as we think this assumption is approximately true, we regard our results as being highly suggestive as well.

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[25] There are some technological optimists who maintain that the premise of *Jurassic Park* is not far from being realizable, but more sober estimates suggest that retreating extinct species will remain the stuff of science fiction for the foreseeable future.

Other omissions and simplifications in our model have likely led us to overestimate the value of the marginal species, however.

One of these omissions concerns timing and discounting. We have assumed that different species are sampled sequentially, but that each is evaluated instantaneously. To have inserted discounting in our simple model would not have complicated matters much; it could be accommodated by multiplying our expression for the value of the marginal species by a discount factor. If, as seems likely, it could take years before the marginal--or "last"--species would even be evaluated, values would be considerably lower.

Of course, research does not proceed by evaluating all samples sequentially. In practice, firms also decide in how much capacity they ought to invest. Firms with greater research capacity can evaluate different species simultaneously. To evaluate a large number of species simultaneously is to increase the probability with which redundant expenses are incurred however.

Redundant expenses are one of the reasons for which a more realistic treatment of market structure might also result in lower estimates of the willingness to pay for the marginal species. Over and above the fear of being beaten to a promising lead by a competitor, rivals may also dissipate values by overinvesting in research and development. There are a number of models in the industrial economics literature [see, e. g., Loury, 1979; Brander and Spencer, 1984] in which firms innovate too fast--incurring too great an expense--in an effort to finish first.

More importantly, our numerical example does not recognize the abundance of potential sources of new pharmaceutical products. In constructing our numerical example we have supposed that all the world's species--and more generally all possible research opportunities--can be separated into those that might possibly yield a product and those that definitely do not. We suspect that restricting our attention to higher plants is very unrealistic. Major pharmaceutical products have been developed from a microorganism first found in the soil of a Japanese golf course and from a spore that happened to float through the window of a laboratory in New Jersey and contaminated an ongoing experiment. Synthetic chemistry and other inorganic sources provide other alternatives. The number of available substitutes maybe much higher than we have supposed.

Finally, we have not included Bayesian updating m our analysis. We have supposed that researchers' beliefs concerning the probability that *any* organic source could contain the product sought do not decline regardless of lack of success. To suppose that downward revisions in expectations would not occur after an unbroken string of failures would imply either a very optimistic investigator or one with a very pessimistic prior; if the latter, one would have to wonder if search would have been undertaken in the first place.

VIII. Conclusions

We have developed a simple model of the demand for indigenous genetic resources for use in pharmaceutical research. We have demonstrated that the upper bound on the value of the marginal species-and by extension of the "marginal hectare" of threatened habitat--may be fairly small under even relatively favorable assumptions. Moreover, the value of the marginal species may be a very sharply peaked function of the probability with which any species chosen at random yields a commercially valuable discovery. Finally, we have argued that our model, even though it is very simple, may yet offer some important insights into the real values that biodiversity prospecting might generate for conservation.

Even if the reader rejects all of our other assertions, we would argue that the development of a model of the demand for genetic resources is an important contribution in and of itself. The valuation of genetic resources for pharmaceutical prospecting is an important issue in conservation policy. Despite numerous contributions from ecologists, environmental advocates, and, recently, economists, there has not yet been any adequate treatment of this subject. Whatever else the drawbacks of our study maybe, we have modeled values with an eye to the importance of scarcity. In addition, several recent papers have advanced economic theories of the measurement of diversity. In none of these instances were these concepts reduced to monetary values, however.

We would also argue that our numerical examples merit serious consideration. It is true that, by making very generous estimates of the profitability of the industry and supposing very fortuitous realizations of the probability of discovery, one might generate moderate estimates for the conservation incentives provided by genetic prospecting. One would have to take a very rosy view to suppose that the probabilities of discovery happen to be precisely those that generate the maximum possible value for the marginal species. If one takes the more reasonable perspective that researchers have some subjective probability distribution over the probability with which individual species sampled will yield commercial products, it seems quite likely that the perceived value of the marginal species will be miniscule. This view seems to be consistent with information concerning observed transactions. This subject should be studied further, and the extensions we have discussed above pursued, but we would not expect a reversal of the conclusion of our analysis, however the value of the marginal species for use in pharmaceutical research, and, by extension, the incentive to conserve the marginal hectare of threatened habitat, is negligible.

We should emphasize again in closing that none of our conclusions imply that we should not be concerned with the problems of declining biodiversity.[26] Our point is, rather, that if the international community values biological diversity, it should be actively seeking other alternatives for financing its conservation.

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[26] We should note in passing that the *social* value of the marginal species for pharmaceutical research may be higher than the private, as a successful researcher cannot appropriate the entire surplus for new drug discovery. This does not detract from our conclusion that private incentive to conserve endangered habitats for Pharmaceutical research will not be great. We doubt, however, that even the social incentives for this purpose would be large.

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Figure 1

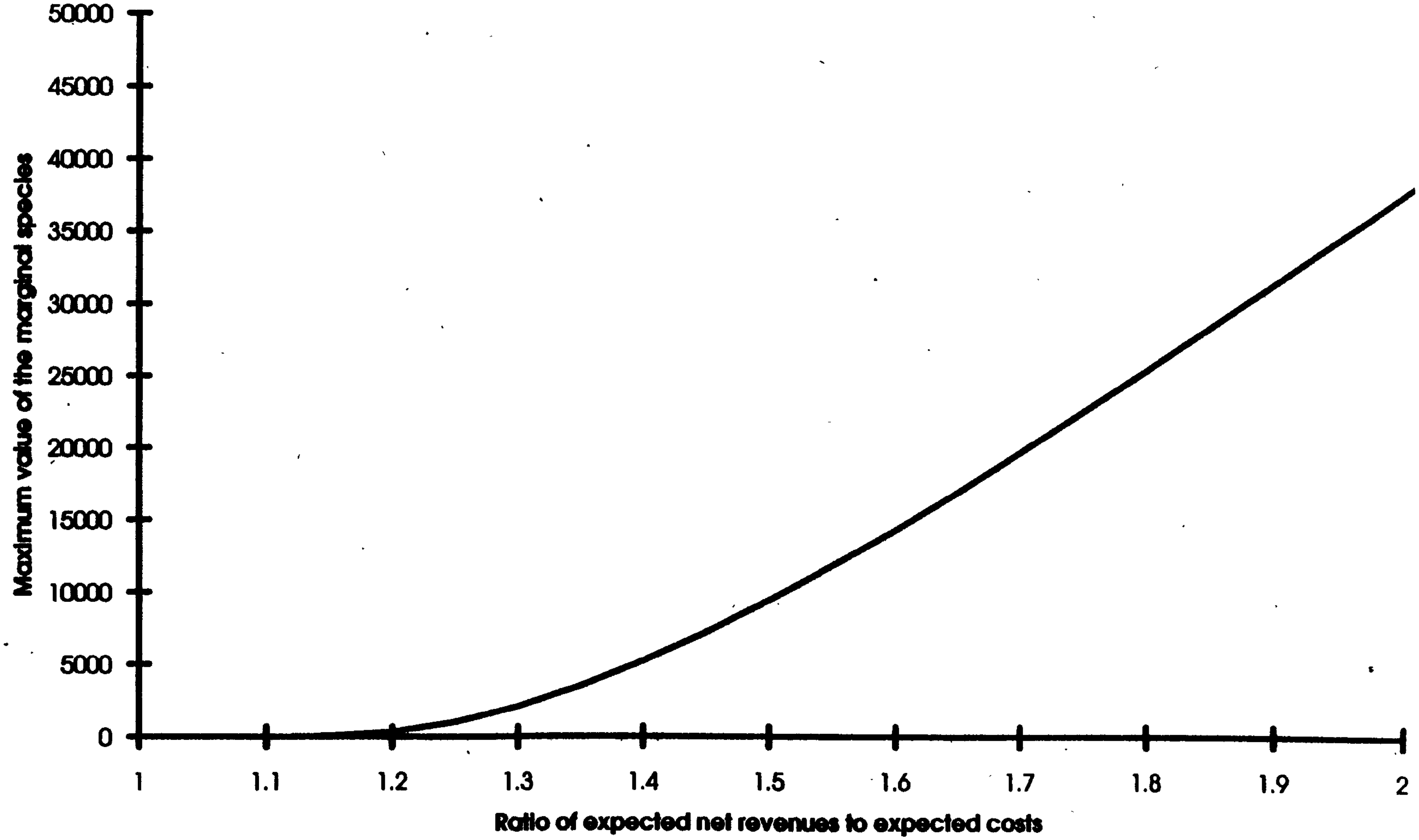
Maximum value of the marginal species
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
Ratio of expected net revenues to expected costs

Figure 2

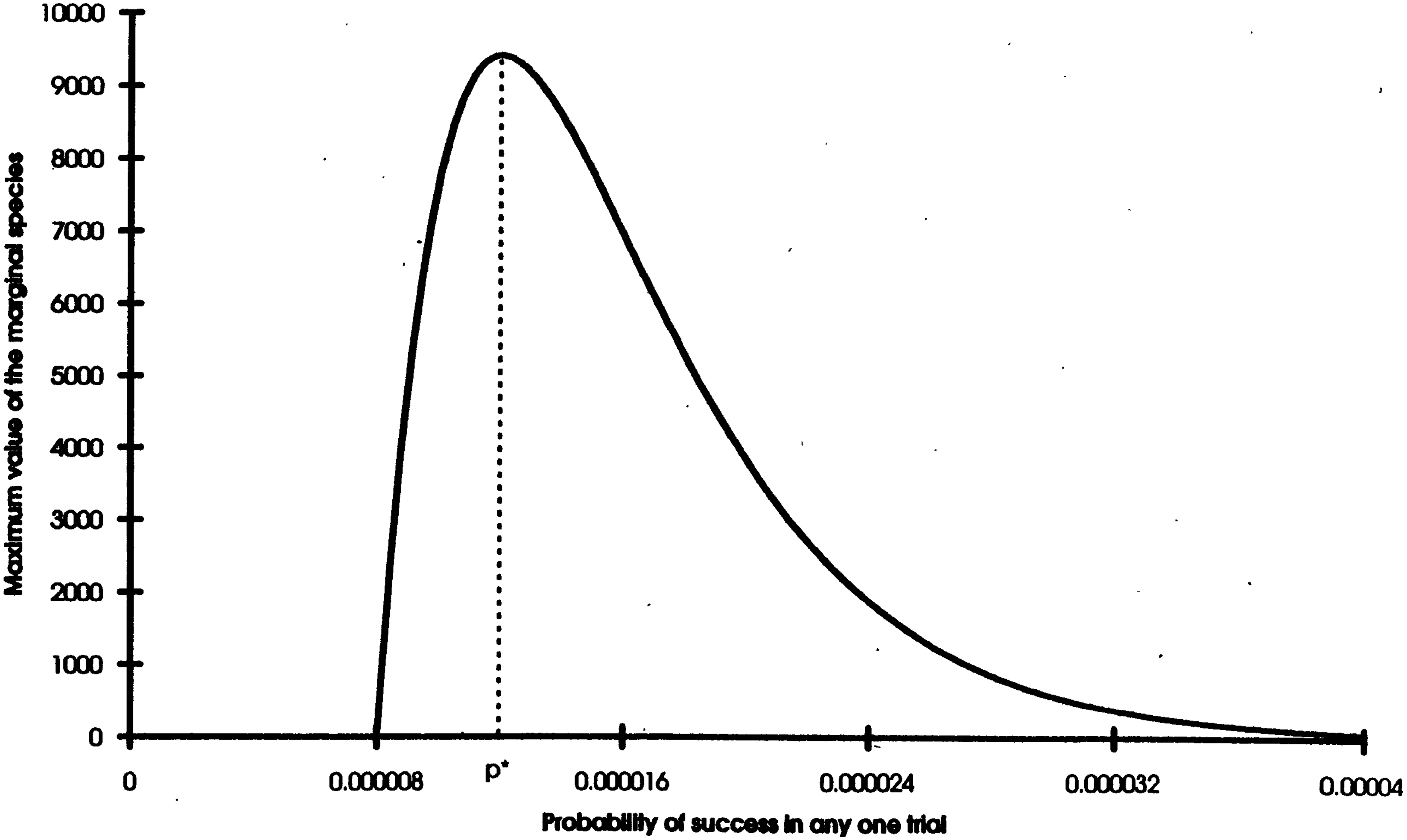
Maximum value of the marginal species
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.000008
p*
0.000016
0.000024
0.000032
0.00004
Probability of success in any one trial

Table 1

New Drug Approvals	
1981	27
1982	28
1983	14
1984	22
1985	30
1986	20
1987	21
1988	20
1989	23
1990	23
1991	30
1992	26
1993	25

Source: U.S. Food and Drug Administration

Table 2

Net revenues and R&D expenses of three major pharmaceutical companies

		1992	1991	1990	1989	1988	1987	1986	1985	1984	1983
Merck											
	Sales	9,622.5	8,602.7	7,671.5	6,550.5	5,939.5	5,061.3	4,128.9	3,547.5	3,559.7	3,246.1
	Materials & production costs	2,096.1	1,934.1	1,778.1	1,550.3	1,526.1	1,444.3	1,338.0	1,272.4	1,424.5	1,263.4
	Marketing & administrative expenses	2,963.3	2,570.3	2,388.0	2,013.4	1,877.8	1,682.1	1,269.9	1,009.0	945.5	905.1
	Research & development expenses	1,111.6	987.8	854.0	750.5	668.8	565.7	479.8	426.3	393.1	356.0
Upjohn											
	Sales	3,668.9	3,426.3	3,032.7	2,732.1	2,530.5	2,292.4	2,063.9	1,800.7	1,695.6	1,557.9
	Materials & production costs	981.6	874.6	823.2	763.9	697.6	655.4	639.2	585.4	566.7	518.1
	Marketing & administrative expenses	1,432.4	1,342.4	1,158.0	1,030.6	932.6	842.3	736.2	633.9	591.5	546.8
	Research & development expenses	548.5	491.1	427.2	407.1	379.7	354.8	313.0	283.2	246.0	217.3
Bristol-Myers Squibb											
	Sales	11,156	10,571	9,741	8,578	7,986	7,044	6,163	5,393	5,029	4,721
	Materials & production costs	2,857	2,717	2,665	2,418	2,255	2,096	1,905	1,769	1,699	1,678
	Marketing & administrative expenses	4,366	4,209	3,906	3,534	3,365	3,002	2,576	2,254	2,110	1,965
	Research & development expenses	1,083	983	873	781	680	556	476	405	337	294

Source: 1992 annual reports of companies

Table 3

Base Case Scenario	
Number of species	250,000
Expected number of new products	10
Cost of developing a new product	$300,000,000
Net revenue-to-cost ratio	1.5
Net revenue	$450,000,000
Discount rate	0.1
c	$3,599.96
p*	0.000012
Probability of a hit	0.9502
λ	10.52
Value of the marginal species	$9,431.16

Table 4

Maximum willingness to pay to preserve a hectare of land in 18 biodiversity "hot spots"

Hot-Spots	Present Forest Area (1000 HA)	Number of Plant Species	Proportion of Plant Species Endemic to Region	Endemic Plant Species per Hectare	Maximum Willingness To Pay
Western Ecuador	250	8,750	0.25	0.00875	$20.63
Southwestern Sri Lanka	70	1,000	0.50	0.00714	$16.84
New Caledonia	150	888	0.89	0.00527	$12.43
Madagascar	1,000	3,550	0.82	0.00291	$6.86
Western Ghats of India	800	4,050	0.40	0.00203	$4.77
Philipines	800	3,595	0.44	0.00198	$4.66
Atlantic Coast Brazil	2,000	7,500	0.50	0.00188	$4.42
Uplands of Western Amazonia	3,500	15,383	0.25	0.00110	$2.59
Tanzania	600	1,600	0.33	0.00088	$2.07
Cape Floristic Province of South Africa	8,900	8,600	0.73	0.00071	$1.66
Peninsular Malaysia	2,600	5,799	0.28	0.00062	$1.47
Southwestern Australia	5,470	3,630	0.78	0.00052	$1,22
Ivory Coast	400	2,770	0.07	0.00048	$1.14
Northern Borneo	6,400	6,856	0.39	0.00042	$0.99
Eastern Himalayas	5,300	5,655	0.39	0.00042	$0.98
Colombian Choco	7,200	9,212	0.25	0.00032	$0.75
Central Chile	4,600	2,900	0.50	0.00032	$0.74
California Floristic Province	24,600	4,450	0.48	0.00009	$0.20

Source: Myers (1988; 1990) and authors' calculations.