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ALTERNATIVE APPROACHES TO ECONOMIC-ENVIRONMENTAL INTERACTIONS

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ABSTRACT

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The key questions raised by recent developments in resource and environmental economics have been what useful economic functions does the environment provide and how are these functions affected by the process of economic-environmental interaction? This paper distinguishes between two different formal approaches to answering these questions: the more conventional approach which is concerned with the optimal allocation of economically valuable exhaustible resources and an alternative analysis that considers the trade-off between, on the one hand, environmental quality, and on the other, resource depletion and waste generation by the economic process. To illustrate and extend the latter approach, a model is constructed to show how this trade-off might lead to continuously declining environmental quality and a future ecological constraint. Society must therefore optimally allocate output between consumption and services to improve the environment and choose between increased capital accumulation and environmental degradation. Although strict application of such a model may be limited, it has wider implications for the role of technological change and the value of the environment in any system experiencing deteriorating environmental quality

INTRODUCTION

Economic analysis of resource and environmental problems has been extensively developed in recent years. To distinguish its general approach from those of other scientific disciplines, this analysis has relied on one guiding principle, i.e. "that the satisfaction of any value requires the use of scarce productive services of some type, and we must necessarily have some way to allocate them" (Herfindahl, 1974a, p. 5). The crucial questions that

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environmental and resource economists have been asking, therefore, are what useful economic functions does the environment provide and how are these functions affected by the process of economic–environmental interaction?

This paper distinguishes between two different formal approaches to answering these questions: the more conventional approach which is concerned with the optimal allocation of economically valuable exhaustible resources [1] and an alternative analysis that considers the trade-off between, on the one hand, environmental quality and, on the other, resource depletion and waste generation by the economic process. To illustrate and extend the latter approach, a model of economic–environmental interaction is constructed to show how this trade-off might lead to continuously declining environmental quality and a future ecological constraint.

Although strict application of such a model may be limited, it has wider implications for the role of technological innovations and the value of the environment in any system experiencing deteriorating environmental quality. The concerns, and indeed some of the propositions suggested in this model, are not new. It builds on earlier attempts to integrate environmental dimensions into growth models, and the experiences learned from incorporating ideas from thermodynamics and ecology into economics. The model of this paper therefore demonstrates the physical dependency of economic activity on the sustainability of crucial natural resource systems and ecological functions, and indicates the economic costs, or trade-offs, resulting from the failure to preserve sustainability and environmental quality. The objective is 'sustainable' growth and development, and it mirrors the increasing concern over new – possibly irreversible – environmental dangers, such as the greenhouse effect, ozone-layer depletion, land degradation, deforestation, and so forth, rather than reiterating the previous concern with material and energy shortages per se. In short, the alternative approach is more applicable to the emerging problems of *environmental degradation*, which require a different method of analysis than the conventional problem of *depletion of a specific resource stock.*

CONVENTIONAL APPROACHES

Following the classic work by Hotelling (1931), the conventional economic approach is to treat natural resources as comparable to other assets of wealth in the economy worth 'holding' in the present. Consequently, the conventional definition of natural resources is usually limited to those environmental resources providing economically valuable productive services

Notes on p. 17.

in the economic system, meaning that only one function of the natural environment – as supplier of the raw material and energy inputs to the economic process – is considered relevant to the phenomenon of natural-resource scarcity. Since they are valuable commodities traded in markets, as these resources become increasingly scarce, their prices will rise relative to those of other goods.

What makes certain material and energy-yielding natural resources worth holding compared to other assets, therefore, is the expected threat of future scarcity from over-exploitation and depletion. Hence the conventional economic approach is to ask what is the optimal rate of extraction or depletion of these economically valuable resources. Ideally, for any particular resource, this will depend on its relative scarcity, and thus (shadow) price, over time compared to other assets (both 'natural' and economic), which in turn should depend on the availability of substitutes, technological innovation, economies of scale, market imperfections, the pattern of property rights and whether the resource is 'renewable'.

The general convention is to "call extractive resources renewable or non-renewable depending on whether they exhibit economically significant rates of regeneration" (Fisher and Peterson, 1977, p. 681). In the case of strictly 'non-renewable' resources, it may be optimal to deplete the resource completely if the availability of future technologies and perfect substitutes mean that exploitation of the resource is no longer 'essential' for future production (Dasgupta and Heal, 1974, 1979; Solow, 1974b; Stiglitz, 1974; Kamien and Schwartz, 1978; Dasgupta and Stiglitz, 1981). That is, because the future scarcity of the resource has been mitigated, the resource is not worth holding compared to other income-earning assets, and the optimal choice may be to exhaust the resource quickly and invest in these other assets. Even in the case of renewable resources, such as a forest valued for its timber, exhaustion may be optimal if the resource is growing at a slow rate, harvesting costs are low and its value appreciates more slowly than the market rate of interest (Clark, 1976; V.L. Smith, 1977).

Thus the conventional approach to natural resource scarcity usually engenders optimism, i.e., "there seems to be little reason to worry about the exhaustion of resources which the market already treats as economic goods" (Nordhaus and Tobin, 1977, p. 402; see also Barnett and Morse, 1963; Beckerman, 1974; Solow, 1974a). For those resources of the environment used as basic material and energy inputs, market forces should dictate the optimal rate of exploitation automatically and effectively. [2]

Notes on p. 17.

ALTERNATIVE APPROACHES

An alternative approach to resource and environmental problems is to recognize that there is not just one but three important functions performed by scarce environmental resources: first, as emphasized by conventional approaches, the environment provides useful material and energy inputs for the economic process; second, the environment assimilates the waste by-products generated by this process; and third, the natural environment provides certain utility-yielding services, or ecological functions, that are essential for supporting the economic system and human welfare. [3] The latter range from recreational, health, cultural, educational, scientific and aesthetic services to the maintenance of essential climatic and ecological cycles and functions (Freeman, 1979; Pearsall, 1984; Barbier, 1989a).

Together, these three economic functions of the environment underline the physical dependency of the economic process and human welfare on ecological stability and the sufficiency of potentially scarce environmental resources. The fundamental scarcity problem, therefore, is that as the environment is increasingly being exploited for one set or uses, say, to provide new sources of raw material and energy inputs and to assimilate additional waste, the quality of the environment may deteriorate over time. The consequence is an increasing 'relative' scarcity of essential environmental services and ecological functions (Barbier, 1989a). In other words, if "the environment is regarded as a scarce resource", then the "deterioration of the environment is also an economic problem" (Hueting, 1980, pp. 1, 3).

Such an approach may lead to applying different criteria for the economic exploitation of environmental resources. For example, where conventional criteria might justify the cutting down of a forest, alternative criteria might justify preservation if the expected loss of value resulting from the decline in genetic diversity, soil quality, ecological stability, natural beauty, etc. were considered too high (Krutilla and Fisher, 1985). In other words, only by looking at the *total economic value* provided by *all* the functions of an environmental asset, is it possible to weigh the environmental benefits of preservation foregone against the net benefits of development (Pearce, Barbier and Markandya, 1990).

There are a growing number of studies emphasizing the environmental costs of economic activity, such as "the transformation and loss of whole environments as would result, for example, from clear cutting a redwood forest, or developing a hydroelectric project in the Grand Canyon" (Fisher, Krutilla and Cicchetti, 1972, p. 605; see also Arrow and Fisher, 1974;

Notes on p. 17.

Krutilla and Fisher, 1985; Miller and Menz, 1979; Turner, 1988; Southgate, 1989). Thus Krutilla and Fisher (1985) demonstrate that irreversible conversion of natural areas in fixed supply may have a high opportunity cost by foreclosing the future option of deriving environmental services from these areas. Other studies have stressed the essential utility-yielding role of natural ecosystems and their environmental functions (Freeman, 1979; Hueting, 1980; Farnworth et al., 1981; Pearsall, 1984; Farber and Costanza, 1987; Turner, 1988; Barbier, 1989a; Barbier and Markandya, 1989). The conventional approach to optimal resource depletion has also been broadened to incorporate the conditions that allow the preservation of natural environments containing resources used as productive inputs (Krautkraemer, 1985; Southgate, 1989), or to embrace an integrated approach to a variety of resource allocation problems (Dasgupta, 1982; V.K. Smith and Krutilla, 1977). In addition, analysis of optimal choice over time among consumption, accumulation and environmental quality has been the focus of a number of studies (Vousden, 1973; Maler, 1974; Becker, 1982; Barbier, 1989a; Barbier and Markandya, 1989). On still a broader front, Norgaard (1984, 1985) discusses the "coevolutionary development" of ongoing feedback and interaction between social and ecological systems, whereby the feedback mechanisms previously maintaining the ecosystem are assumed by or shifted to the social system.

The model of this paper follows, and hopefully clarifies, these approaches by addressing a situation where economic-environmental interaction not only leads to increasing 'relative' scarcity of utility-yielding environmental services, but as environmental quality declines, there is also the possibility of widespread ecological disruption and disturbances. That is, in the long run, an absolute ecological constraint may arise because the increasing environmental degradation inflicted by the economic process irrevocably disrupts natural ecosystems. Permanently impairing essential environmental functions on which economic activity and human welfare depend (Daly, 1979; Barbier, 1989a).

Such a model may be appropriate in cases where cumulative resource depletion and waste generation by the economic process lead to severe ecological disruption and the collapse of human livelihoods. For example, with continuous tropical deforestation, there may be adverse local and interregional ecological disturbances that radically alter rainfall patterns, climate and species diversity. The result may be a catastrophic decline in the ability of the forest area and neighboring regions to support dependent economic systems and human populations (Myers, 1984; Sioli, 1985; Southgate, 1989). Similarly, climatic changes resulting from excess emission of greenhouse gases from industrial activity may significantly affect agricultural productivity and thus the ability of some regions of the world to feed their populations (Oram, 1985; Barbier, 1989b). Intensive agricultural production on marginal lands can lead to accelerating problems of soil erosion, watershed degradation and even desertification (American Farmlands Trust, 1984; Barbier, 1988; Nelson, 1988; Southgate, 1988). Long-term combustion of fossil fuels emitting SO_x and NO_x pollution may increase 'acid rain' to levels intolerable for forest and freshwater ecosystems, thus destabilizing livelihoods dependent on fishing and forestry activities (WRI/IIED, 1986, chapter 10).

A MODEL OF ECONOMIC-ENVIRONMENTAL INTERACTION

The following model analyzes the prospect of irreversible damage to the natural environment arising from resource depletion and waste generation; the outcome is a steady decline in environmental quality leading to potential long-run disruptions to important ecological systems and functions. In order to capture these 'relative' and 'absolute' scarcity impacts of increasing environmental degradation over time, several assumptions are adopted.

First, to indicate the dependency of human welfare on essential environmental services and ecological functions, a stock variable representing environmental quality, X_t, [4] is included along with consumption, C_t, as arguments in the social welfare function, U:

$$U = U(C_t, X_t) \tag{1}$$

with $U_c(C_t) > 0$, $U_{cc}(C_t) < 0$, $U_x(X_t) > 0$, $U_{xx}(X_t) < 0$. Equation (1) indicates that at any time t social welfare is a concave, increasing function of consumption and environmental quality. To simplify analysis, the welfare function is additively separable, i.e.

$$U_{cx} = U_{xc} = 0$$

Second, it is assumed that at any time t any output, Q_t, produced by the economic system that is not used for consumption, for providing environmental improvement services, V_t, or for replacing depreciated capital, wK_t, leads to a net accumulation in the capital stock, $K_t - K_{t-1}$:

$$K_t - K_{t-1} = Q_t - (C_t + V_t) - wK_t \tag{2}$$

Capital depreciates at the constant rate w. Environmental improvement services can be divided between those that directly improve environmental quality through, say, conservation practices, resource management, pollution clean-ups etc., and those that indirectly improve X_t by increase recycling and abatement of waste residual otherwise emitted into the environment.

Notes on p. 17, 18.

Third, following the 'relative' scarcity argument of the 'alternative' approach, it is assumed that at any time t as the economic process extracts resources, R_t, from the environment and generates (net) waste, N_t, increasing environmental degradation, $S_t - S_{t-1}$, occurs and, as a result, environmental quality declines:

$$S_t - S_{t-1} = f(R_t, N_t) \tag{3}$$

$$X_t = X(S_t, V_t) \tag{4}$$

$$X_t < X_{t-1} \tag{5}$$

with $f_r(R_t) > 0$, $f_n(N_t) > 0$, $X_s(S_t) < 0$ and $X_v(V_t) > 0$. Equation (4) shows that environmental quality is a decreasing function of environmental degradation, S_t, and an increasing function of environmental improvement services, V_t. A crucial assumption is that, since $S_t - S_{t-1} > 0$ throughout any time period t, then X_t must also be declining (conditions 3 and 5). That is, environmental degradation occurs each period because the economic process must require some resource inputs, R_t, for production and generate some net waste, N_t. However, to suggest that the result is lower environmental quality each period implies that: (a) the level of environmental improvement services, V_t, is insufficient to counteract the increased environmental degradation, and (b) ecosystems are unable to 'repair' the resulting damage to crucial functions, cycles and resources through converting the energy flow from the sun or utilizing any inputs of material and energy from neighboring ecosystems. These are clearly strong assumptions that may not hold for all economic–environmental systems. [5]

Fourth, in order to incorporate the 'absolute' ecological constraint discussed above, the life of the economic–environmental system is assumed to be finite, where terminal time T is that period at the end of which environmental degradation reaches some maximum level, $\bar{S}$, driving environmental quality to some minimum level, $\underline{X}$, and thus irrevocably destabilizing the entire economic-environmental system. This constraint on the system can be summarized as:

$$t_0 \leq t < T, \qquad \underline{X} < X_t \quad \text{and} \quad U = U(C_t, X_t) \tag{6}$$

$$\lim_{t \to T} t, \qquad \lim_{S_t \to \bar{S}} X(S_t), \qquad \underline{X} \quad \text{and} \quad \lim U \to 0$$

The size of the population and its growth often impact on the environment. However, in this approach this affect has been left our of consideration.

Notes on p. 18.

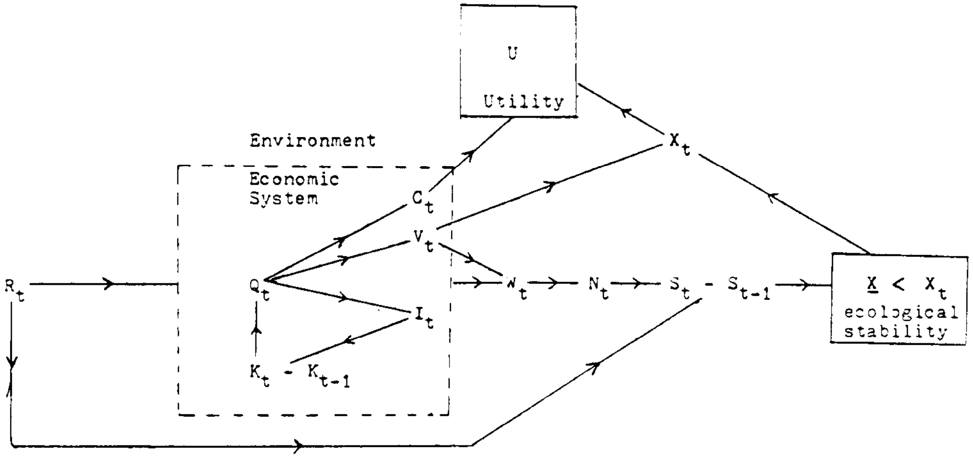

Fig. 1. Flow diagram of economic-environmental interaction.

Assuming population growth is constant, the remaining functional relationships of the model can be simplified to:

$$Q_t = Q(K_t) \quad \text{with} \quad Q_k(K_t) > 0 \text{ and } Q_{kk}(K_t) < 0^6 \tag{7}$$

$$R_t = R(Q_t) \quad \text{with } R_q(Q_t) > 0 \tag{8}$$

$$N_t = W(Q_t) - B(V_t) \tag{9}$$

with $B_v(V_t) > 0$, $B_{vv}(V_t) < 0$ and $W_q(Q_t) > 0$. That is, production is a function of the capital stock; resource use and waste generation, W_t, are functions of total output; and net waste generation is W_t less any recycling, B_t.

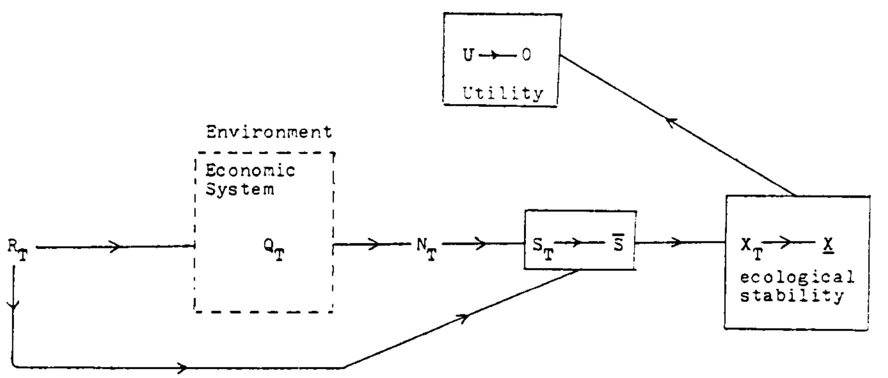

Fig. 2. Long-run ecological constraint.

Notes on p. 18.

Finally, the initial and terminal conditions of the model are respectively:

$$K_0 = \underline{K}, \qquad S_0 = \underline{S} \tag{10}$$

$$K_T \geq \bar{K} \geq 0, \qquad S_T \geq \bar{S} \tag{11}$$

The functional relationships of the model for period $t_0 \leq t \leq T$ are summarized in Fig. 1, and the operation of the absolute constraint in period T is shown in Fig. 2.

OPTIMAL ALLOCATION OVER TIME

Thus the planning problem suggested by the model is how best to allocate economic and environmental resources over time given the current 'relative' scarcity problem of declining environmental quality and the threat of a future ecological constraint on the entire system. A dynamic discrete time optimization problem can be constructed from the model with the aid of a few substitutions.

Substituting (7)–(9) into (3) yields:

$$S_t - S_{t-1} = f(R(Q(K_t)), W(Q(K_t)) - B(V_t)) = g(K_t, V_t) \tag{12}$$

with $g_k(K_t) > 0$ and $g_v(V_t) < 0$. That is, as capital accumulation leads to production growth and – in the absence of technological change – more resource throughput, whereas environmental improvement services reduce waste through recycling, then environmental degradation is essentially an increasing function of K_t and a decreasing function of V_t at time t.

Expressions (12) and (4) can be substituted for X_t in the social welfare function (1), which is now summed over the finite planning period $[t, T]$ and discounted at the rate $0 < r < 1$:

$$U = \sum_{t=1}^{T} \frac{1}{(1+r)^{t-1}} U(C_t, X(S_{t-1} + g(K_t, V_t), V_t)) \tag{13}$$

A Lagrangean function, L^*, can now be formed from (13), (2), (10) and (11):

$$\begin{aligned} L^* = & \sum_{t=1}^{T} \frac{1}{(1+r)^{t-1}} U(C_t, X(S_{t-1} + g(K_t, V_t), V_t)) \\ & + \sum_{t=1}^{T} p_t(K_{t-1} + Q_t(K_t) - (C_t + V_t) - wK_t - K_t) \\ & + p_0(\underline{K} - K_0) + p_{T+1}(K_T - \bar{K}) + u(\underline{S} - S_0) + a(S_T - \bar{S}) \end{aligned} \tag{14}$$

The Lagrangean multiplier p_t can be interpreted as the utility value of an additional unit of capital, i.e. the social value of capital accumulation that becomes available in period t. Similarly, the multiplier u represents the social value of an increase in the initial level of environmental degradation,

S_0, whereas a indicates the social value of a 'relaxation' in the binding terminal constraint, as represented by an increase in $\bar{S}$.

Thus the dynamic optimization problem is to maximize (14) by optimal choice of C_t, V_t and K_t. Assuming C_t, V_t, K_t and $S_t > 0$, the first-order conditions are:

$$\frac{\mathrm{d}L^*}{\mathrm{d}C_t} = \frac{1}{(1+r)^{t-1}} U_c(C_t) - p_t = 0 \qquad t = 1, \ldots, T \quad (15)$$

$$\frac{\mathrm{d}L^*}{\mathrm{d}V_t} = \frac{1}{(1+r)^{t-1}} U_x(X_t)\left(X_s(S_t)\, g_v(V_t) + X_v(V_t)\right) = 0 \qquad t = 1, \ldots, T \quad (16)$$

$$\frac{\mathrm{d}L^*}{\mathrm{d}K_t} = \frac{1}{(1+r)^{t-1}} U_x(X_t)\, X_s(S_t)\, g_k(K_t) + p_{t+1} - p_t + p_t(Q_k(K_t) - w) = 0 \qquad t = 1, \ldots, T \quad (17)$$

$$\frac{\mathrm{d}L^*}{\mathrm{d}K_0} = p_1 - p_0 = 0 \quad (18)$$

$$\frac{\mathrm{d}L^*}{\mathrm{d}S_0} = U_x(X_1)\, X_s(S_1)\,(1 + g(K_1, V_1)) - u = 0 \quad (19)$$

$$\frac{\mathrm{d}L^*}{\mathrm{d}S_T} = \frac{1}{(1+r)^{T-1}} U_x(X_T)\, X_s(S_T) + a = 0 \quad (20)$$

As specified, the complexity of the model prevents characterization of a final solution to these equations. Interpretation of these conditions, however, does provide some useful insights into society's allocative choices when faced with the unique 'relative' and 'absolute' scarcity constraints of the model. For example, condition (15) can be substituted into condition (16) to yield:

$$\frac{U_c(C_t)}{U_x(X_t)} = X_s(S_t)\, g_v(V_t) + X_v(V_t) \qquad t = 1, \ldots, T \quad (21)$$

This suggests that the marginal rate of substitution of X_t for C_t is equated in each period with the impacts on the environment of a marginal increase in environmental improvement services. These services either protect the environment directly, $X_v(V_t)$, or indirectly by recycling waste and thus reducing some of the negative impact of the economic process on the environment, $X_x(S_t)\, g_v(V_t)$. Thus condition (21) defines the optimal trade-off between increased consumption and provision of services to improve the environment. That is, at any time $t = 1, \ldots, T$ any allocation of output between C_t and V_t must obey this rule.

Condition (17) can be rearranged as:

$$p_{t+1} - p_t = p_t(Q_k(K_t) - w) + \frac{1}{(1+r)^{t-1}} U_x(X_t)\, X_s(S_t)\, g_k(K_t) \qquad t = 1, \ldots, T \quad (22)$$

which indicates that the social value of capital is changing in each period according to the benefits of marginal capital productivity net of depreciation, $p_t(Q_k(K_t) - w)$, less the discounted marginal damage of the environmental degradation accompanying this increased productivity, $U_x(X_t)\, X_s(S_t)\, g_k(K_t)$. Capital accumulation that is not replacing depreciated stock leads to increased output and thus socially valuable consumption and environmental improvement services. At the same time, however, the increased output requires a greater use of resources by the economic system, which in turn increases environmental degradation. The former can be considered the benefits of capital accumulation and the latter the costs. If in any period the costs exceed the benefits of capital accumulation, then its social value will decline. If the costs equal the benefits, the value remains constant, i.e.

$$\text{if} \quad p_t(Q_k(K_t) - w) = \frac{1}{(1+r)^{t-1}} U_x(X_t)\, X_s(S_t)\, g_k(K_t)$$

$$\text{then} \quad p_{t+1} - p_t = 0 \qquad t = 1, \ldots, T \quad (23)$$

Expressions (22) and (23), therefore, are the rule governing the optimal rate of capital accumulation, and thus growth, in the economy.

Condition (18) states that the social value of additional capital in the first planning period and the period before are equal; i.e., the social value of capital is unchanged up to the first period. Condition (19) shows that the negative social value of a decline in the initial state of the environment must be equal to the marginal damage of an increase in environmental degradation in the first period. Any such increase in S_0 must be a social cost, for it both lowers initial environmental quality, X_1, and it brings the system that much closer to the level of environmental degradation that causes its 'collapse', $\bar{S}$. In contrast, an increase in $\bar{S}$ would prolong the life of the economic–environmental system and is therefore beneficial to society. From condition (20), this benefit is equivalent to the marginal utility of a decrease in environmental degradation in the last period.

To summarize, this model has derived the optimal conditions for allocating economic and environmental resources in an interdependent economic–environmental system where any resource depletion and waste generation by the economic process leads to deteriorating environmental quality and an eventual ecological collapse. As the model has stressed that the state, or quality, of the environment is an essential determinant of social welfare, environmennetal improvement services are recognized as a socially valuable component of economic output, and in every period, society must optimally allocate output between consumption and services to improve the environment. Although the key to expanding output is capital accumulation, the cost of capital accumulation and production growth is increased environmental degradation. If this cost exceeds the benefits of economic expansion, then the social value of capital accumulation and thus growth declines. Under certain conditions determining the social welfare function, e.g., individuals' giving more weight to environmental quality than consumption in their utility considerations, society may opt for slower or for even no production growth and to allocate an increasing share of output to environmental improvement services. Such allocative choices are clearly consistent with a preference for ecological preservation over increased aggregate consumption, a preference that is perhaps spurred by apprehension over the type of future 'absolute' ecological constraint included in this model.

Thus the quantitative results of the model clearly depend on: (a) the relative preferences of individuals, (b) the development of technology, and (c) the resilience and regenerative capacity of ecosystems and life-support functions. It is to these wider issues that the paper now turns.

WIDER IMPLICATIONS: TECHNOLOGY, TASTES AND TIME

As noted in section one, conventional approaches to natural resource scarcity often indicate that technological innovation, substitution and improvements in resource management can be mitigating factors in overcoming increasing relative scarcity. The crucial question is whether the type of scarcity effects envisioned by the above model can also be mitigated by technological innovations and proper environmental management. The answer must be yes, albeit with some qualifications. One key is, of course, slowing down the rate of environmental degradation to a level low enough that there is little appreciable or significant deterioration in vital ecological functions or natural resource systems. As suggested by equation (3) of the model, this invariable calls for innovations that can slow down the rate of resource throughput in the economy by reducing the inflows of material and energy required from the environment and the outflows of waste. There are essentially two broad types of resource-saving innovations that can be applied to economic activity:

(1) Resource-saving innovations in the process of production:

(a) *factor-substitution*, e.g. labor-power for energy, resource-saving capital for energy and materials;

(b) *reuse of scrap and waste materials*, i.e. improvements in recovery and recycling producer and consumer waste;

(c) *increased efficiency of resource conversion and utilization*, i.e. obtaining the maximum amount of end-use energy and material for production of final goods and services from the primary inflows of resources into the economic system.

(2) Other resource-saving innovations:

(a) *improved organizational techniques*, i.e. better organization of production, distribution and consumption activities to reduce resource inefficiencies and resource use;

(b) *changes in the composition of output*, e.g. from non-durables to durables, from resource-using goods to services, etc.;

(c) *changes in product quality and/or design*, e.g. reducing sizes and weights of vehicles, eliminating 'built-in-obsolescence', re-designing throwaway packages and containers, improving energy-efficiency in appliances, etc.

The technology necessary to achieve these resource-saving innovations may already exist, or is easily achievable, in the advanced industrialized countries. As a recent report from the U.S. Office for Technical Assessment (OTA, 1988) has indicated, thanks to the revolution in information technology, resource savings of 40–60% of current use could be *feasible* in the near future for the United States *without* any sacrifice in economic growth. However, as Page (1977) has emphasized, what is technologically feasible in terms of resource saving may not actually be realized unless some conservation criterion, such as keeping the resource base intact for future generations, is accepted as a valid macro-economic policy goal. Perhaps the recent policy debate over the use of a 'carbon tax' to reduce emissions, encourage resource-saving innovations and thus mitigate any possible CO_2-induced 'global warming' is one indication that policy makers are increasingly taking into account long-term considerations of future economic security and welfare.

As implied by equation (4), better techniques of environmental improvement and management could also mitigate any decline in envrionmental quality. The quality of the environment will generally be improved by a variety of innovations ranging from improvements in resource, land and water management to developments in ecologically appropriate planning of tourist facilities, conservation areas and environmental policies to the dissemination of new conservation skills and training. Particularly in the case of agricultural systems, where "ecosystems are transformed into hybrid agroecosystems for the purpose of food or fibre production" (Conway, 1985, p. 34), the result may also be a direct increase in production. For example, in the Sahel small farmers struggle to produce a predominantly millet-based cropping system under conditions of drought, high temperature and marginal soil fertility. Through the introduction of improved multi-cropping techniques, new drought and pest-resistant varieties of cowpeas and no-tillage mulching, water run-off and soil erosion were reduced and yields increased (IITA, 1985, pp. 22–26). Similar examples from around the world show how improved land-management techniques and cropping systems – accompanied by appropriate economic policies, incentives and investment strategies – can overcome land and watershed degradation (American Farmlands Trust, 1984; Barbier, 1988; Nelson, 1988; Southgate, 1988).

Despite optimism that the combination of resource-saving and environmental management techniques could indefinitely postpone the type of binding ecological constraint suggested by condition (6), there a number of reasons why such innovations may not be 'automatically' or 'effectively' implemented in response to declining environmental quality.

First, in the conventional case of increasing scarcity of raw materials, the existence of identifiable markets for these resources means that the price system can automatically respond to this increasing scarcity and thus induce the appropriate innovative responses. However, many environmental resources exist outside the economic system as integral components of complex resource and ecological systems, and are thus nonmarketed common property resources. Although "markets indirectly and other institutions directly influence the allocation of these resources" for use as resource inputs and waste assimilation as opposed to preservation, "unfortunately none of these can be relied upon to provide the information on the marginal valuations of the resources involved in these allocations" (Smith and Krutilla, 1979, p. 281). As Pearce (1985, p. 21) has argued, even if external environmental costs imposed by resource depletion are estimated, "there is nothing in the conventional concept of an external costs to account for the decay of ecological processes themselves", and as a result, "in the absence of perfect information and both perfect and instantaneous response to ecological disequilibrium, the system can be unsustainable." Without a mechanism for conveying this information, the appropriate technological response to environmental degradation is not assured.

Furthermore, the appropriateness and effectiveness of technological innovation in halting environmental deterioration depend on a clear understanding of the ecological impacts of pollution and resource depletion. However, changes in the state of the environment and its resources usually involve substantial qualitative changes and interactions. The aggregate effects on ecological functions and systems may in some cases by an unusual capacity for resilience and regenerative capacity, whereas in others, a tendency towards rapidly reinforcing disturbance and disruption (Conway, 1985). Because such changes are rarely stable, frequently irreversible and often cumulative and discontinuous, environmental systems almost never 'settle' to an equilibrium state in response to perturbations and disturbances. Even in the relatively simple case of a constant input of pollution into a stream ecosystem, the environmental system may or may not reach an equilibrium condition for years, as the pollutant may differentially affect the survival rate and perhaps even the course of evolution of species in the stream. In the case of multiple pollutants, the combined changes rarely equal the sum of the separate effects (Norgaard, 1985, p. 384).

In addition, there may be physical limits on the extent to which resource-saving innovations can reduce resource throughput in the economic process. It may be possible, as noted above, to reduce current U.S. resource use by 40–60% and still have reasonable economic growth, but any further reductions may not be feasible under even the most optimistic technological assumptions. As argued by Daly (1977, 1979) and Georgescu-Roegen (1971, 1979), the source of these restrictions stem from the first and second laws of thermodynamics as analogously applied to the economic process:

(1) from the first law, as material and energy can neither be created nor destroyed, production and consumption must require some inputs of material and energy from the environment and generate some waste.

(2) from the second law, as material and energy used in transformation must irrevocably dissipate or decay, some degradation of material and energy from a useful to a useless state by the economic process is inevitable and irreversible.

In other words, resource-saving innovations may minimize, but they cannot eliminate, resource throughput in the economic process. Given uncertainty over ecological processes and environmental change, even the minimum resource-throughput level required to sustain an economic process may continue to damage the environment, particularly if it has been subject to stress from past resource-using technologies for a significant period of time, or if the regenerative capacity/resilience of affected ecosystems is low. Many current environmental problems, such as the global greenhouse effect, land degradation in resource-poor areas, deforestation and so forth, contain elements of this problem.

Finally, just as conditions (21)–(23) indicate that optimal allocation of output between consumption, environmental improvement services and investment is influenced by the relative preferences of consumption to environmental quality and changes in the social value of capital, choices of resource-saving and environmental management innovations over other possible technological 'mixes' will be dictated by individuals' tastes and preferences. The classic problem here, of course, is that choice of innovations today will affect both future consumption and environmental quality, yet there is no method available to measure the intensity of future preferences and the preferences of future generations. For example, very little of the yield-enhancing technical progress in U.S. agriculture over the postwar period was induced by concern about the cumulative effects of soil erosion, and has thus contributed to the current problems of soil degradation on erodible croplands, which is now an urgent and pressing concern (Crosson and Stout, 1983). In assessing both future and present reactions to environmental degradation, the crucial problem remains that "the level of the shadow price of environmental functions is largely indeterminate because insufficient information is available on the preferences for environmental functions" (Hueting, 1980, p. 141).

In sum, resource-saving technological and environmental management innovations should in principle be capable of overcoming the type of scarcity effects depicted by the model of this paper. However, because the main indicator of these scarcity effects – the relative decline in the quality of the environment and ecological functions – occurs largely outside the institutional mechanisms of the economic system, and at best, is only indirectly and partially captured by the market through impacts on productivity, human health, resource management costs, etc., the appropriate innovative responses may not be automatically forthcoming. Moreover, given the complexity of ecological relationships, their often unstable responses to stresses and shocks, the uncertainty over future and even current preferences for environmental functions and resources, and the physical limits to resource-saving techniques, the effectiveness of innovations in ameliorating environmental deterioration may be constrained. If this is the case, then the trade-off between consumption and environmental improvement services, and between more production growth and increased environmental preservation, suggested by conditions (21)–(23) may be unavoidable.

SUMMARY AND CONCLUSION

The model of this paper has confirmed the general conclusion of many alternative approaches to natural resource scarcity that if individuals express preferences for essential environmental resources and functions which are perceived to be deteriorating over time, then it may be optimal to consider trade-offs between consumption and services to improve the environment and between more rersource-using growth and environmental preservation. With its strong assumption of increasing environmental degradation leading to ecological collapse, the model may be strictly applicable to only a limited number of economic–environmental systems. Its general insights. however, are more widely applicable to any situation where economic activity leads to declining environmental quality and loss of ecological functions. To borrow Hueting's (1980) phrase, this is the "new scarcity" that is affecting all global systems, including the advanced industrialized economies. Given the uncertainties surrounding appropriate and effective innovative responses, there must be concern that "we could get into serious difficulty simply because of inability to cope in time with... deterioration in the quality of the environment" (Herfindahl, 1974b, pp. 272–273). As "no one model provides the means for understanding how the ends of both economic growth and ecological sustainability might be achieved" (Norgaard, 1985, p. 388), further developments in both the conventional and alternative approaches described in this paper are necessary for improving our understanding of the complex interaction between economic and environmental systems.

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NOTES

[1] According to Dasgupta and Heal (1979, p. 3), "a resource is exhaustible if it is possible to find a pattern of use which makes its supply dwindle to zero.

[2] As Dasgupta and Heal (1979, pp. 5–7) point out, however, although in theory "capital-resource substitution may be sufficient to overcome the 'drag' imposed by an essential and exhaustible resource", in practice this requires "a complete set of forward markets", a condition which "is certainly not met" in actual market systems, and "as a consequence resource markets may be unstable, and will almost certainly display 'market bias', in the sense of depleting the resource at a rate different from an optimal rate". Quite clearly, the problem is "uncertainty about future resource stocks and about future technology."

[3] d'Arge (1972) provides an alternative classification of these functions into four categories: "(a) source of raw materials; (b) space for waste accumulation and storage; (c) assimilation-regenerative capability for chemically or biologically active wastes; and (d) determinant of health and life style, and of aesthetic satisfactions."

[4] Following Becker (1982) and Maler (1974), it is assumed that environmental quality is measured by a stock of environmental goods that yield a flow of services proportional to that stock in each time period. However, Becker (1982) defines this stock variable as "the differences between the level of pollution for which life ceases and the current level of pollution." Similarly, Maler (1974) in his intertemporal models considers that only the quality and flow of waste residuals and recycling have an impact on environmental quality. Here, it is assumed that environmental quality may be effected not only by (net) waste generation but also by resource depletion and services to improve the environment, such as conservation and resource management. For a given type of ecosystem with its associated energy flow, a measure of environmental quality may include, in addition to Becker's definition, the ecosystem's biomass (i.e., the volume or weight of total living material found above or below ground) plus some measure of the distribution of nutrients and other materials between the biotic (living) and abiotic (nonliving) components of the ecosystem. Such a measure is discussed in more detail in (Barbier, 1986, chapter 8), and is more consistent with this model's

broader concept of deteriorating environmennetal quality, or environmental degradation, which "comprises not just the loss of environmental quality that impinges on the senses, but also the damage to the damage to the natural purification and regenerative processes of the environment itself" (Pearce, 1985, p. 21).

[5] In fact, it may be possible to make this condition explicit by constructing an index of environmental degradation that is proportional to some measure of R_t and N_t (Barbier, 1986, chapter 8).

[6] Note that, as discussed above and indicated in Fig. 1, some beneficial services of the environment, such as maintenance of soil, air and water quality or of climatic stability, directly aid economic production. This would suggest that environmental quality, X_t, should also be included in the production function for economic output, Q_t. Recent discussions of the 'sustainability' of production in the Third World imply this relationship (Conway, 1985; Pearce, Barbier and Markandya, 1989). However, to simplify analysis in this model, the more traditional production function for the economy is employed. Instead, the stream of benefits provided by environmental quality to production activities are included as part of the overall contribution of X_t to welfare. Hence, X_t in equation (1) can be interpreted as representing both the direct utility-yielding impacts of environmental quality on individuals and the indirect impacts on overall social welfare through assisting production and other intermediate economic activities. This in any case may be a more appropriate way of accounting for these latter services, as their benefits are often 'externalities' to private production and consumption allocation decisions.

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