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THE CONDITIONS FOR ACHIEVING ENVIRONMENTALLY SUSTAINABLE DEVELOPMENT

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1. Introduction

A review of the literature on 'sustainable' economic development suggests that two interpretations of that concept have emerged: a wider concept concerned with sustainable economic, ecological and social development and a more narrowly defined concept largely concerned with 'environmentally sustainable development', i.e. with optimal resource and environmental management over time.[2]

This paper is interested in the 'narrower' interpretation - the relationship between environmental quality and sustainable economic activity. The latter is interpreted as that level of economic activity which leaves the environmental quality level intact, with the policy objective corresponding to this notion being the maximization of net benefits of economic development, subject to maintaining the services and quality of natural resources over time.[3]

The term 'natural resources' is used broadly. It includes renewable resources, such as water, terrestrial and aquatic biomass; non-renewable resources, such as land in general, minerals, metals and fossil fuels; and semi-renewable resources, such as soil quality, the assimilative capacity of the environment and ecological life support systems.

Consequently, maintaining the services of a natural capital stock does not necessarily imply maintaining this physical stock of composite resources intact, which in any case, may not be desirable or feasible for non-renewables. On the other hand, keeping the level of environmental quality intact implies caution in assuming that an irreversible loss of the natural capital stock is justified if it results in the formation of more man-made capital. Some of the functions of the environment are not replicable by reproducible capital, such as complex life support systems, biological diversity, aesthetic functions, micro-climatic conditions and so forth. Others might be substituted but not without unacceptable cost. In addition, degradation of one or more parts of a resource system beyond some threshold level may lead to a breakdown in the integrity of the whole system, dramatically affecting recovery rates and resilience of the system. The total costs of the system breakdown may exceed the value of the activity causing the initial degradation.[4]

Thus under certain conditions maximizing the net benefits of economic development, subject to maintaining the services and quality of the stock of natural resources over time, is an essential criterion for sustainable development. As Pearce and others have consistently argued, this criterion requires observation of certain biophysical constraints.[5] That is, if the resource base is a composite of exhaustibles and renewables (including semi-renewables and waste-assimilative capacity), sustainability requires:

(a) utilizing renewable resources at rates less than or equal to the natural or managed rates of regeneration;

(b) generating wastes at rates less than or equal to the rates at which they can be absorbed by the assimilative capacity of the environment; and

(c) optimizing the efficiency with which exhaustible resources are used, which is determined, inter alia, by the rate at which renewable resources can be substituted for exhaustibles and by technological progress.

Failure to obey these constraints will lead to a process of environmental degradation as the resource base is depleted, wastes accumulate and natural ecological processes are impaired. This of course assumes that:

(a) the services, or functions, of the environment are essential to the economic system;

(b) there are insufficient substitution possibilities between reproducible capital and these environmental functions; and

(c) these environmental functions are not augmented by a constant positive rate of technical progress.[6]

The conditions governing the optimal trade-off between environmental quality and consumption over time have been analyzed in various models of economic-environmental interaction.[7] Although these models assume some form of environmental degradation process, and thus implicitly assume transgression of biophysical constraints by the economic system, no attempt is made to examine explicitly how an economy might respond to the limits imposed by these constraints and hence the conditions for optimal sustainable economic growth. In the next section, a simple model is developed to characterize the conditions necessary to maintain the environmental sustainability of an economic system over time.

2. A Model of Environmentally Sustainable Economic Activity

The following model will be used to analyze optimal growth paths for an economy faced with the choice of operating under the three long-term biophysical constraints: harvesting of renewable resources within their natural and managed rates of regeneration; extracting exhaustible resources at the rate at which renewables can be substituted for them (which over the long run implies a zero rate of exhaustion of the 'composite' resource); and emitting wastes within the assimilative capacity of the environment.

The key to the following model is a particular definition of environmental degradation. At any time t, the rate of degradation $\dot{S}$ is a function of: (i) the flow of waste (W) in excess of the amount assimilated by the environment (A) and (ii) the flow of renewable resources harvested from the environment (R) in excess of the (managed or natural) biological productivity of these resources (G), plus the flow of exhaustible resources extracted from the environment (E). Mathematically, this may be written as:

$$\dot{S} = f([W - A], [(R - G) + E]). \qquad (1)$$

The following assumptions are made about (1):

(i) It is a differentiable, increasing function of its arguments. As the net waste level increases and as the excess rate of harvesting increases, so does the level of environmental degradation.

(ii) It is a convex function of its arguments. This can best be illustrated in Figures 1-3. As net wastes emitted increase, so the rate of degradation increases at an increasing rate (Figure 1). The same applies to net resources harvested (Figure 2). However, there is also a trade-off between these two factors that influence the environment. To attain a constant level of degradation, one can reduce the net harvesting of resources if one increases the net levels of waste generated. But the reduction in harvested resources required as one increases the net waste generated itself increases (Figure 3).

(iv) The combinations of [W - A] and [(R - G) + E] that achieve zero degradation are given by the locus of points going towards the origin in Figure 3. Thus a sufficient condition for zero degradation is W = A and

$(R + E) = G$.[8]

Note that, as stated, equation (1) is `symmetrical'; that is, if the biophysical constraints are observed (i.e., $W \leq A$ and $(R + E) \leq G$) in the long run), then the rate of environmental degradation will be zero or there may be an `improvement' in environmental quality.[9] These effects will be made more explicit in the next section. However, it is worth noting that observed environmental impacts are more likely to be `asymmetrical'; i.e., in some economic-environmental systems, it may take a long time before adherence to these biophysical constraints leads to any improvement in environmental quality, whereas failure to observe these constraints may cause rapid environmental degradation.

Having defined the level of environmental degradation as a function of net waste generation and net resources consumed, we now wish to link it to the level of economic activity (consumption) and the "stock" of environmental assets available. We label each of these respectively as C and X, and postulate the following fuctions with the following properties.[10]

$$W = W(C), \quad W'(C) > 0, \quad W''(C) > 0 \tag{2}$$

$$R = R(C), \quad R'(C) > 0, \quad R''(C) > 0 \tag{3}$$

$$E = E(C), \quad E'(C) > 0, \quad E''(C) > 0 \tag{4}$$

$$A = A(X), \quad A'(X) > 0, \quad A''(X) < 0 \tag{5}$$

$$G = G(X), \quad G'(X) > 0, \quad G''(X) < 0. \tag{6}$$

In other words W, R and E are increasing convex functions of C, and A and G are increasing concave functions of X. The concept of environmental quality adopted by this model is fairly broad and essentially synonymous with the entire stock of environmental goods. The three basic functions, or 'services', of this stock are the assimilation of waste, the production of material and energy inputs for the economic system and the provision of amenity, life support and general 'ecological' services. This allows the model to assume that, for all intent and purposes, A and G are increasing functions of X. The assumption that W, R and E are all increasing functions of economic activity are well known results stemming from material-balance models.[11] In addition, the assumption of the convexity of waste generation, W(C), and the concavity of assimilative capacity, A(X), is consistent with the models developed by Forster, which examined optimal economic growth under one set of these biophysical constraints, namely that waste levels should not exceed the assimilative capacity of the environment.[12] Similarly, standard models of renewable resource harvesting assume concave growth functions, G(X), and convex harvesting rates, R(C).[13]

Substituting (2)-(6) into (1) yields an equation in which dS/dt is a function of C and X. Since A and G are concave functions, it follows that -A and -G are convex. Hence dS/dt, which is an increasing convex function of its original arguments, [W - A] and [(R - G) + E], will also be a convex function in its transformed state, as a function of C and X. This can be written as

$$\dot{S} = h(C, X), \tag{7}$$

with $h_c > 0$, $h_{cc} > 0$, $h_x < 0$ and $h_{xx} > 0$ and $h_{cc}h_{xx} - h_{xc}^2 > 0$.

A typical set of contours of (7) are given in Figure 4. As consumption increases, so the environmental quality adjusted stock required to keep the level of degradation constant increases at an increasing rate. In addition to the assumed shape of the X,C contours, we would impose some minimum value on X. This we would define as the minimum environmental stock that provides a viable base for sustained economic activity. In terms of equation (7), this restriction can be written

$$\dot{S} = h(C, X), \qquad X \geq \underline{X} \qquad (7)'$$

$$\dot{S} \gg 0, \qquad X < \underline{X}.$$

Finally, a link can be established between $\dot{S}$, the rate of environmental degradation, and $\dot{X}$, the rate at which environmental quality is changing. Clearly, the basic relationship is an inverse one: as the degradation increases so the environmental stock declines. Assuming both are measured in comparable units, we can represent this by

$$\dot{X} = -a\dot{S} \qquad (8)$$

$$\dot{X} = -ah(C, X), \qquad X \geq \underline{X} \qquad (9)$$

$$\dot{X} \ll 0, \qquad X < \underline{X},$$

where a is a constant scalar.

Figure 1. dS/dt and (W - A)

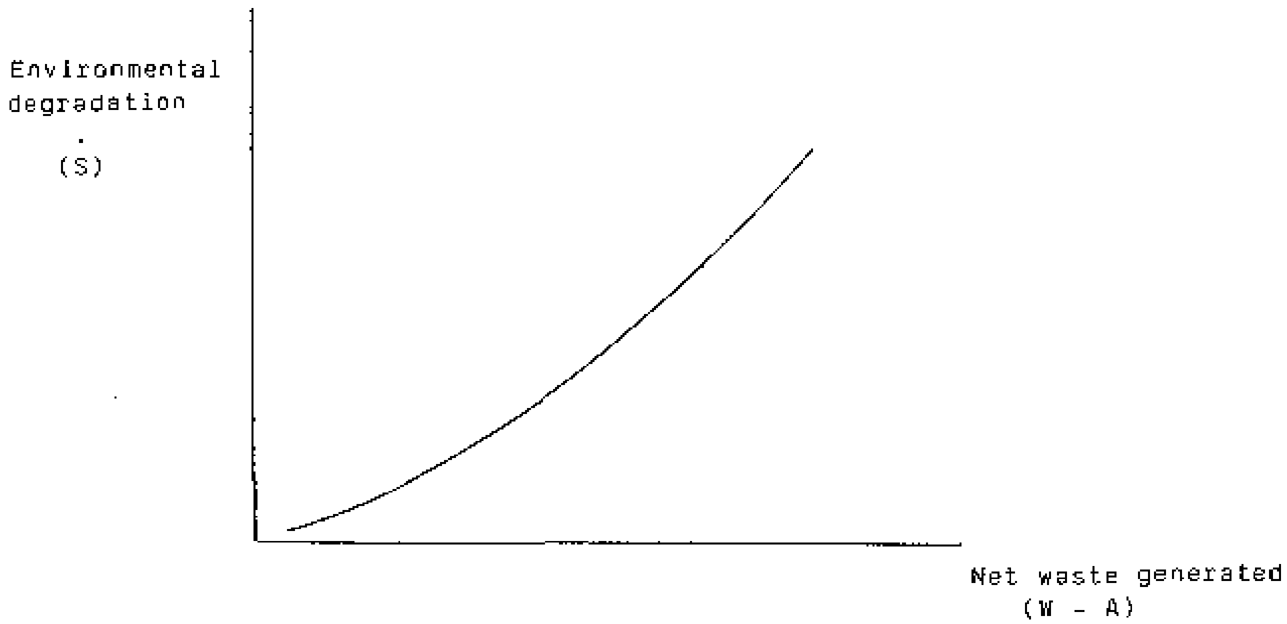


Figure 2. dS/dt and (R + E) - G

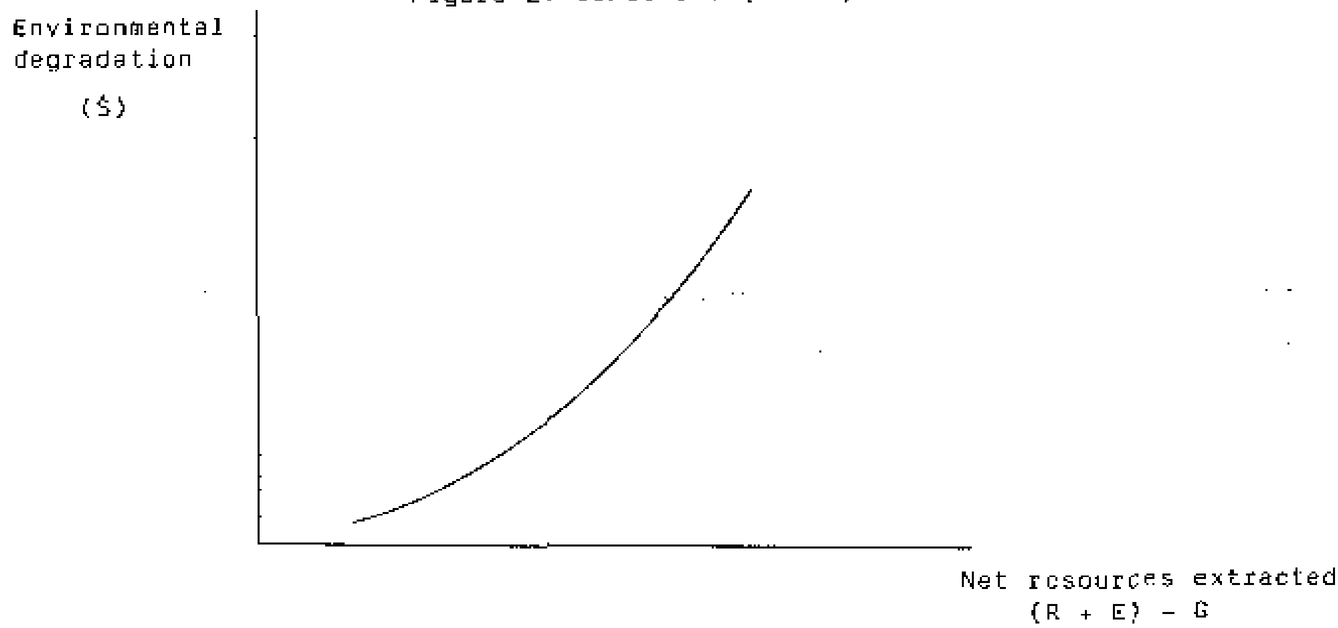
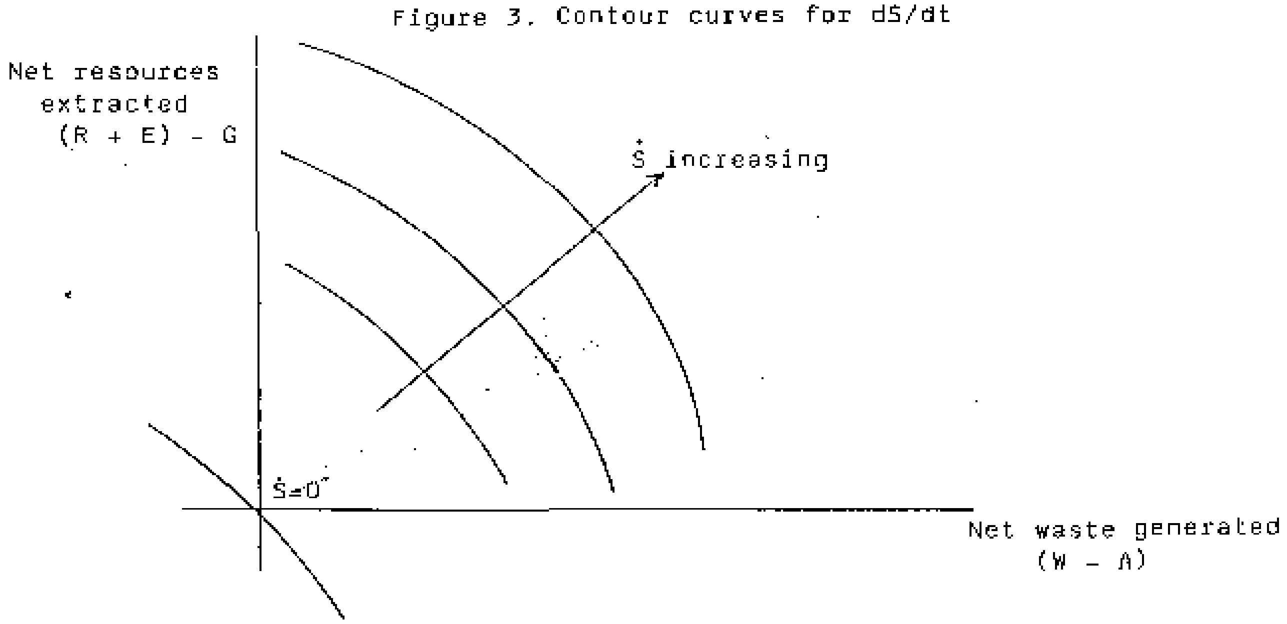


Figure 3. Contour curves for dS/dt



The dynamics of these relationships can best be illustrated in the case of agriculture - or perhaps more appropriately agro-ecosystems - as one is talking about systems that are directly dependent on environmental resources and essential ecological functions for `sustainability'. Thus, for example, Conway has employed the concept of `resilience' as the basis of his definition of agricultural sustainability - "the ability of a system to maintain its productivity when subject to stress or shock."[14] Unchecked resource abuse within an agro-ecosystem, whether the result of inappropriate use of agro-chemicals and feritilizers, overcropping of erodible soils, poor drainage, etc., can affect overall agro-ecosystem sustainability by increasing the susceptibility to stress, shock, or both. The key is reducing the resource degradation, and therefore the stresses and shocks associated with it, to a level where the natural processes and functions of the agro-ecosystem - appropriately subsidized by human-made inputs and innovations - can counteract these disturbances and thus preserve overall sustainability.

Alternatively, one can draw an analogy with standard renewable resource problems, where the rate of biological productivity is assumed to be a function of the stock level, or with pollution problems, in which the rate at which pollution `decays' is also assumed to be a function of the stock level.[15] For example, in the standard renewable resource problem, there is always assumed to be a threshold level below which the population is doomed. At stock levels above this threshold level the rate of growth increases, but at a diminishing rate. Similarly, in pollution models with non-constant decay functions, it is usually assumed that the more pollution the faster it is dissipated, albeit at a diminishing rate. At some maximum threshold level of pollution, the natural clean-up processes in the environment are completely destroyed.

Finally, Barbier has applied a relationship similar to (9) in a model of soil erosion in the uplands of Java.[16] Here, the environmental stock variable, X, is a measure of soil depth, which is degraded at an accelerating rate by the use of a conventional cropping system and is augmented by the use of an alternative soil conservation package. In this system, the *cross-partial derivatives between these two arguments of the function h were considered to be negative.*

3. Optimal Sustainable Economic Growth

Using the above model, it is now possible to explore the conditions for environmentally sustainable growth. For example, it is assumed that social welfare at any point in time is measured by a strictly concave utility function U of current C and the current stock of X:

$$U = U(C,X), \tag{10}$$

with $U_c > 0$, $U_{cc} < 0$, $U_x > 0$, $U_{xx} < 0$, $U_{cx} = 0$, $\lim_{C \to 0} U_c = \infty$, and $\lim_{X \to 0} U_x = \infty$.

Equations (1) and (7) were deliberately constructed to reflect the sustainability criteria of observing the biophysical constraints. That is, a minimum condition for an economic growth path to be sustainable over the long run is $W = A$, $R + E = G$, which ensures that no environmental degradation will occur, i.e., $\dot{S} = 0$. Thus one possible choice open to society is to plan for a growth path that in the long run produces zero environmental degradation.

Conditions (8) and (9) also indicate, however, that as long as some (net) environmental degradation is continuing to occur, environmental quality will decline. Equation (9) suggests that there is a lower limit to environmental quality. As noted above, if X is driven below $\underline{X}$, environmental degradation will have destroyed the natural clean-up and regenerative processes in the environment. This is tantamount to an environmental 'collapse', and economic growth leading to such a collapse can be said to be environmentally 'unsustainable'. Nevertheless, there may be conditions under which society may have no choice but opt for an unsustainable growth path.

However, in general, there will also be conditions leading society to a sustainable growth path. The pursuit of sustainability inevitably involves some intertemporal trade-offs between levels of consumption and environmental quality. For example, in Figure 4, the C-X curve traces for every level of environmental quality the 'sustainable' level of consumption that

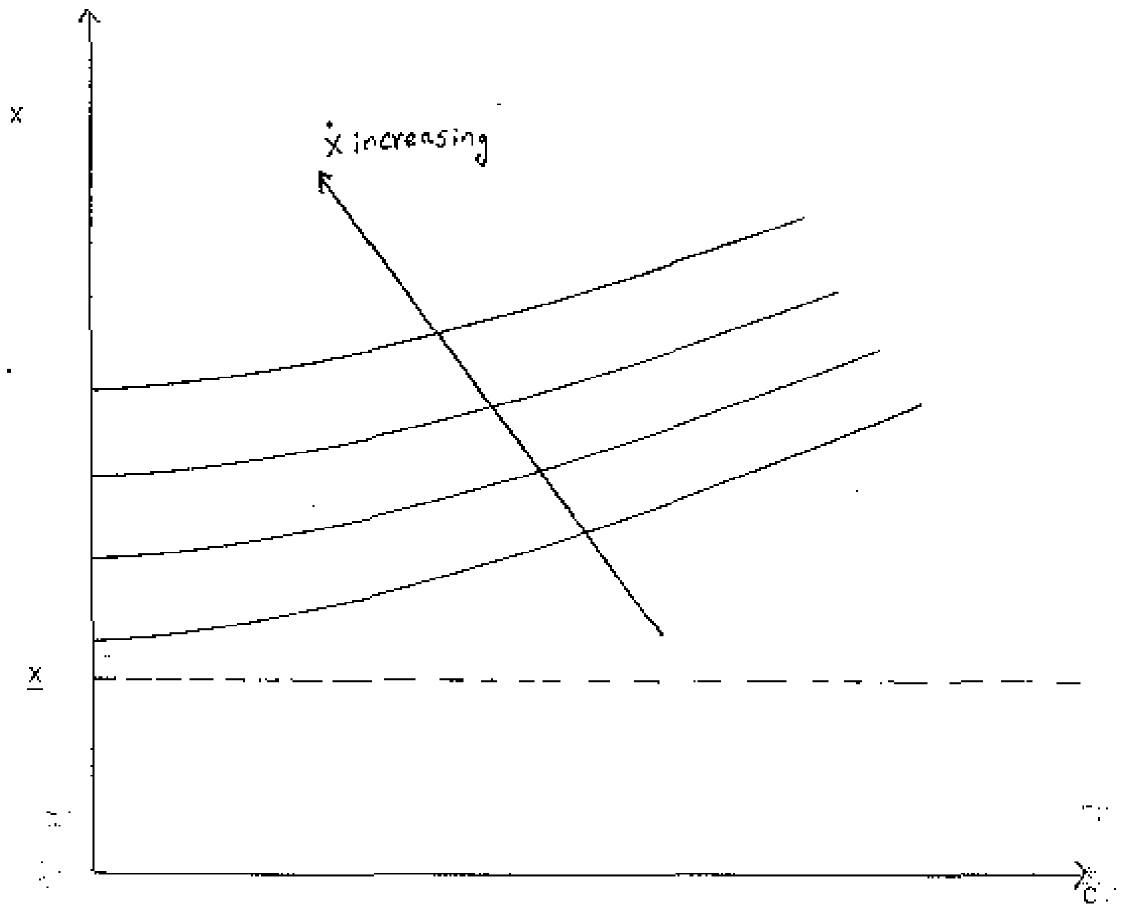


Figure 4. C,X loci for given dX/dt

just leaves environmental degradation unchanged. Thus if at a given level of environmental quality, X_0, one consumes less than the sustainable level of consumption, C_0, then the environment will improve and society will be able to sustain higher level of consumption in the future. Hence, there is, in this intertemporal sense, a positive relationship between increases in consumption (i.e., growth) and improvements in the environment.

However, the convexity of the C-X locus indicates that, as society sacrifices consumption now, so the improvements in the environment get smaller and smaller. On the other hand, the value of that sacrifice increases because of a diminishing marginal rate of substitution between consumption and environmental goods (i.e. the convexity of the indifference curve). Presumably then there would be a point where the two would balance out. In the long run equilibrium, the utility value of a unit of consumption sacrificed today should equal the discounted present value of the higher consumption and environmental quality afforded in perpetuity to future generationss. The higher the discount rate, the less the latter would be and so the equilibrium would be at a lower point on the C-X curve. This is because the benefits of a unit of consumption in terms of the higher X value its permits fall as C falls.

We therefore examine further the optimal conditions leading to sustainable versus unsustainable economic growth. Given a positive rate of time preference, r, the planning problem is to find solutions which will

$$\max \int_0^{\infty} e^{-rt}\, U(C,X)\, dt \qquad (11)$$

subject to $\dot{X} = -\,ah(C,X)$,

$X(t=0) = X_0$, $X(t=\infty)$ free, $X \geq \underline{X}$.

Given the continuous function P(t), the Hamiltonian of the problem is:

$$H = e^{-rt}\{U(C,X) + P[-ah(C,X)]\}. \qquad (12)$$

The first-order conditions for an interior solution are:

$$\frac{dH}{dC} = U_c - Pah_c = 0, \qquad (13)$$

$$\text{or} \quad P = U_c/ah_c > 0,$$

and

$$\dot{P} - rP = -\frac{dH}{dX} = -U_x + Pah_x, \qquad (14)$$

$$\text{or} \quad \dot{P} = [r + ah_x]P - U_x,$$

and

$$\dot{X} = -\,ah(C,X). \qquad (15)$$

P(t) is the costate variable, which can be interpreted as the social value, or shadow price, of environmental quality. Condition (13) gives C as an explicit function of P and X with:

$$\frac{dC}{dP} = \frac{ah_c}{U_{cc} - Pah_{cc}} < 0, \qquad (16)$$

and

$$\frac{dC}{dX} = \frac{Pah_{cx}}{U_{cc} - Pah_{cc}} > 0, \qquad (17)$$

if $h_{cx} < 0$. As will be discussed below, the latter is important with respect to the comparative static analysis of the equilibrium.

From (14) and (15), the behavior of the system from any initial point, (X_0, P_0), is governed by:

$$\dot{P} \gtreqless 0 \quad \text{as} \quad [r + ah_x]P \gtreqless U_x, \qquad (18)$$

$$\dot{X} \gtreqless 0 \quad \text{as} \quad h(C,X) \gtreqless 0. \qquad (19)$$

Note also that from applying (9) to (19):

$$\text{if} \lim_{X \to \underline{X}^+} h(C,\underline{X}) \longrightarrow \infty, \quad \dot{X} \longrightarrow -\infty, \qquad (20)$$

or alternatively, given some large number N,

$$\text{if} \lim_{X \to \underline{X}^+} h(C,\underline{X}) \longrightarrow N, \quad \dot{X} \longrightarrow -N, \qquad (21)$$

then as $X \longrightarrow \underline{X}$, $\dot{X} = 0$ cannot be satisfied. It also follows from (18) that

$$\text{if} \lim_{X \to \underline{X}^+} h_x(C,\underline{X}) \longrightarrow 0, \quad rP = U_x(\underline{X}) \text{ for } \dot{P} = 0, \qquad (22)$$

$$\text{or} \quad P = U_x(\underline{X})/r .$$

Thus an interior solution to the problem must satisfy (18) and

(19) with equality, as well as conditions (20)-(22). The slopes of the stationary loci satisfying these equations are given by:

$$\left.\frac{dP}{dX}\right|_{\dot{P}=0} = \frac{U_{xx} - Pah_{xx} - Pah_{xc}\,dC/dX}{[r + ah_x] + ah_{xc}\,dC/dP} \qquad (23)$$

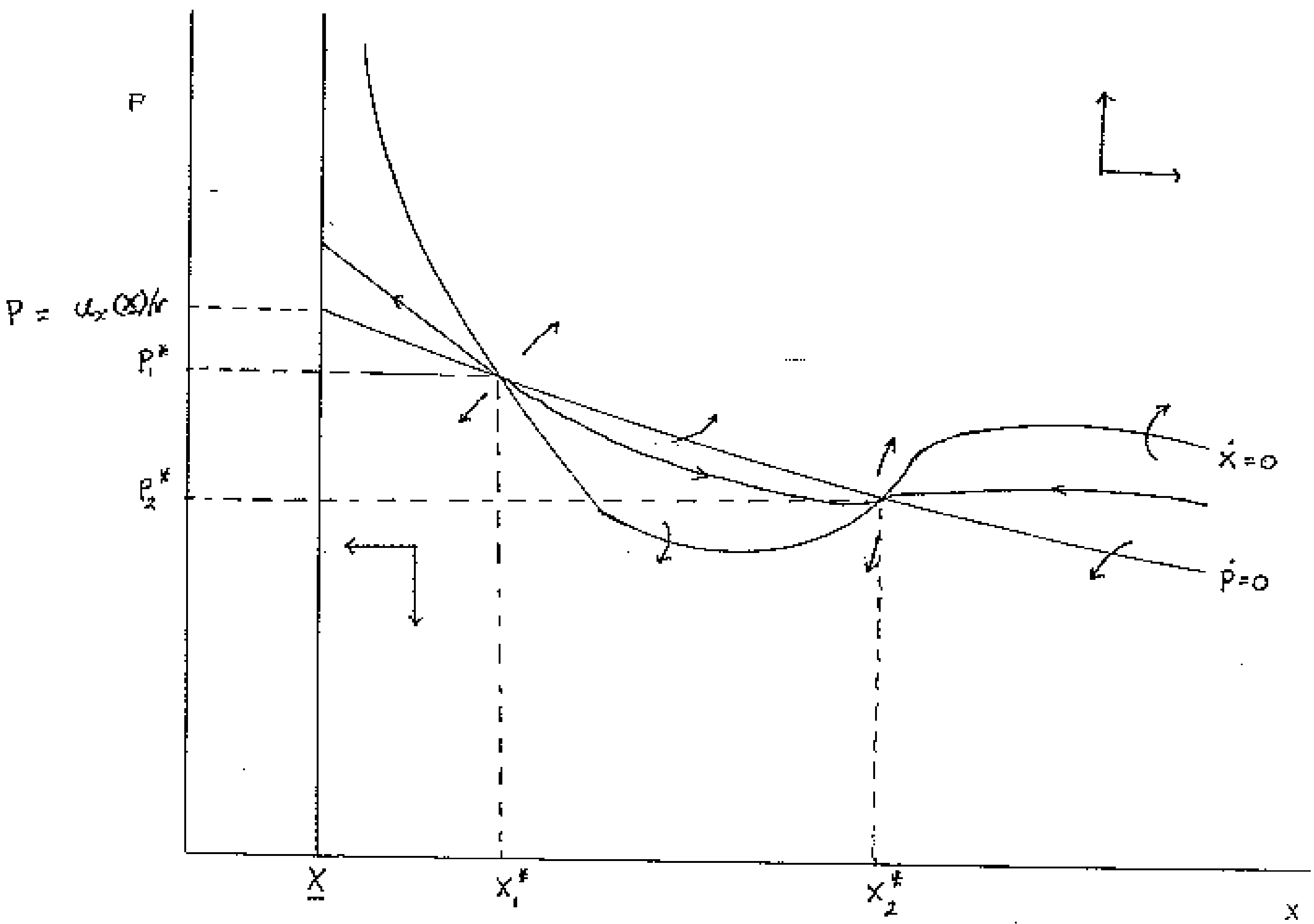
and

$$\left.\frac{dP}{dX}\right|_{\dot{X}=0} = \frac{-[h_x + h_c\,dC/dX]}{h_c\,dC/dP}, \qquad (24)$$

which cannot be definitely signed. One possible configuration of the phase diagrams satisfying (18)-(22) is depicted in Figure 5, to illustrate a stable and an unstable solution.

In Figure 5, (X_2^*, P_2^*) is a stable equilibrium, whereas (X_1^*, P_1^*) is unstable. If $X_o > X_1^*$, then the optimal policy is to select P_o so as to place the economy on a growth path that ends at the stable equilibrium (X_2^*, P_2^*). This represents an environmentally `sustainable' growth, given the assumption that if $\dot{X} = 0$ and $X > \underline{X}$, then biophysical constraints are being observed. If $X_o = X_1^*$, then it is optimal to remain at X_1^* forever. If $X_o < X_1^*$, assuming conditions (20)-(22) are satisfied, then the growth path of the economy could lead to $\underline{X}$. However, this growth path is unsustainable, for at $\underline{X}$, the assimilative and regenerative capacity of the environment will have been destroyed, and the economy will be forced to consume existing internal resource stocks. Eventually, the latter will be consumed and the economy will collapse. Thus X_1^* can be considered the <u>minimum</u> initial level of environmental quality required to ensure a sustainable growth path.

Figure 5. Dual Equilibria Solution to Phase Diagram



Thus with a low initial level of environmental quality, environmentally unsustainable economic growth may be an optimal strategy. Since the benefits of increased consumption occur in the present whereas environmental degradation and collapse is a future problem, this strategy is made optimal by a high rate of discount on future utility. Consequently, both the initial level of environmental quality as well as the rate of social discount are significant factors in determining the optimal choice between sustainable and unsustainable growth as one would expect.

These intuitive results have been shown to be correct if the relationship between the rate of environmental degradation, consumption and the stock of environmental assets takes a particular form. We have assumed, as seems normal, that other things being equal the rate of degradation increases as the level of consumption increases and as the stock of environmental assets declines. In addition, however, we are required to assume that the increase in the rate of degradation as consumption increases is higher with smaller environmental stocks than with larger ones. This is the economic/ecological interpretation of the requirement that $h_{cx} < 0$. Note that the latter is a sufficient condition for the stable equilibrium to occur with a larger environmental stock at a lower discount rate, and for the unstable equilibrium to occur at a smaller environmental stock in the same circumstances.

For example, it is apparent from (18) that an increase in the discount rate would have the effect of shifting down the

$\dot{P} = 0$ curve. As shown in Figure 6, the end result may be a unique equilibrium, but one that is stable only if $X_0 \geq X_3^*$. However, if $X_0 < X_3^*$, it may be optimal to choose an unsustainable growth path; i.e., one that heads towards $\underline{X}$. Note that, as $X_3^* > X_1^*$, an economy with an increased discount rate requires a higher minimum initial level of environmental quality to avoid a growth path that might be environmentally unsustainable.

In contrast, lower discount rates would shift the $\dot{P} = 0$ curve up, requiring a lower minimum initial level of environmental quality to ensure sustainable growth (i.e., $X_5^* < X_1^*$). These results appear to confirm the conclusions discussed above of the role of discount rates in determining the sustainability of the economic process.

It can be confirmed that the minimum bound on the social rate of time preference, r, is not independent of the historically given level of environmental quality, X_0. Note that in (18), for $\dot{P} = 0$ it is a requirement that $r > -ah_x$. Given the properties of h(C,X) outlined in (7), a lower initial X will cause $-ah_x$ to rise, thus requiring a higher r to keep $\dot{P} = 0$. Conversely, a higher X_0 will have a lower rate of discount. As shown in Figure 7, therefore, the initial level of environmental quality imposes a lower limit on the choice of r.

Figure 6. The Effects of Changes in r

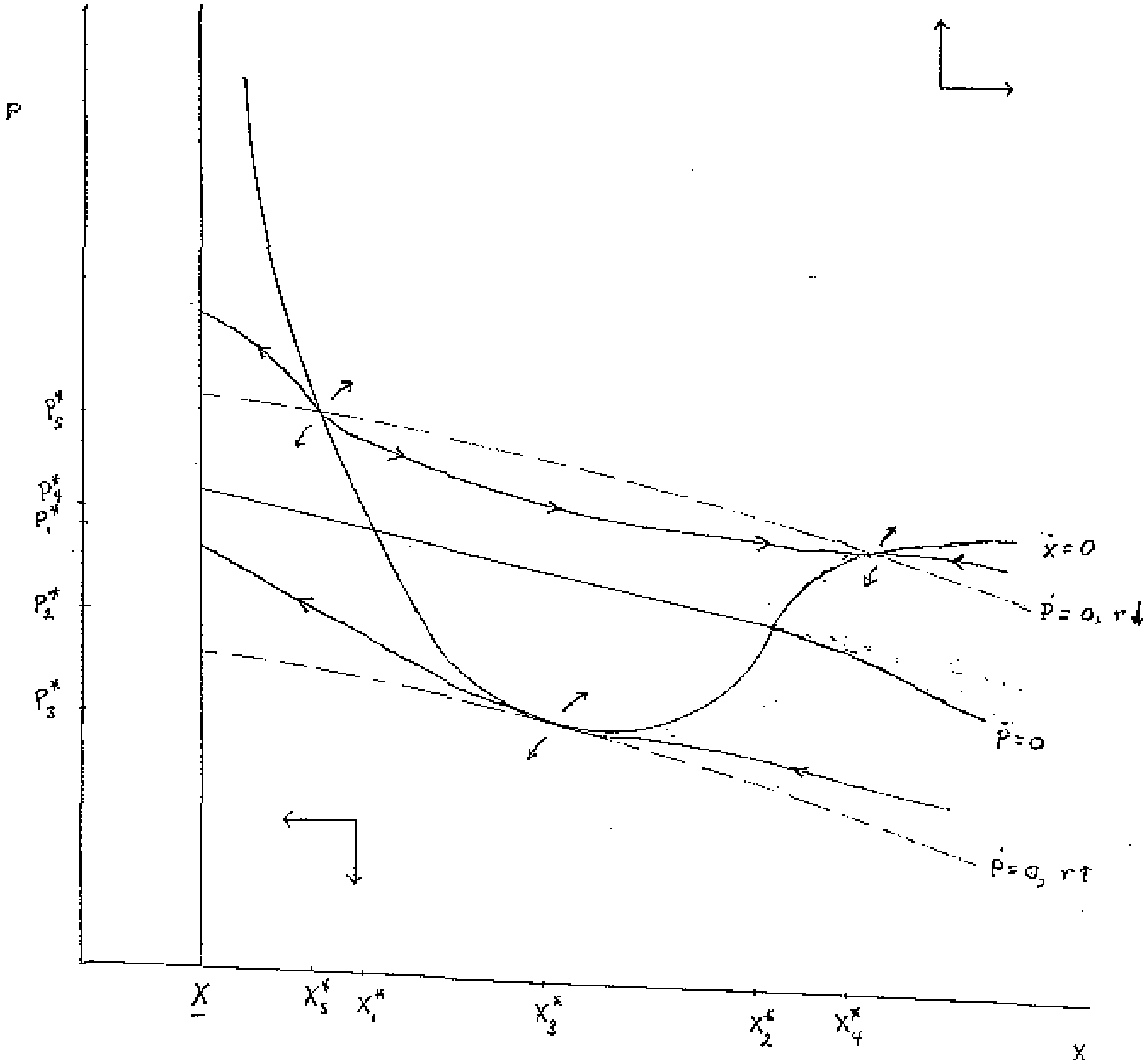
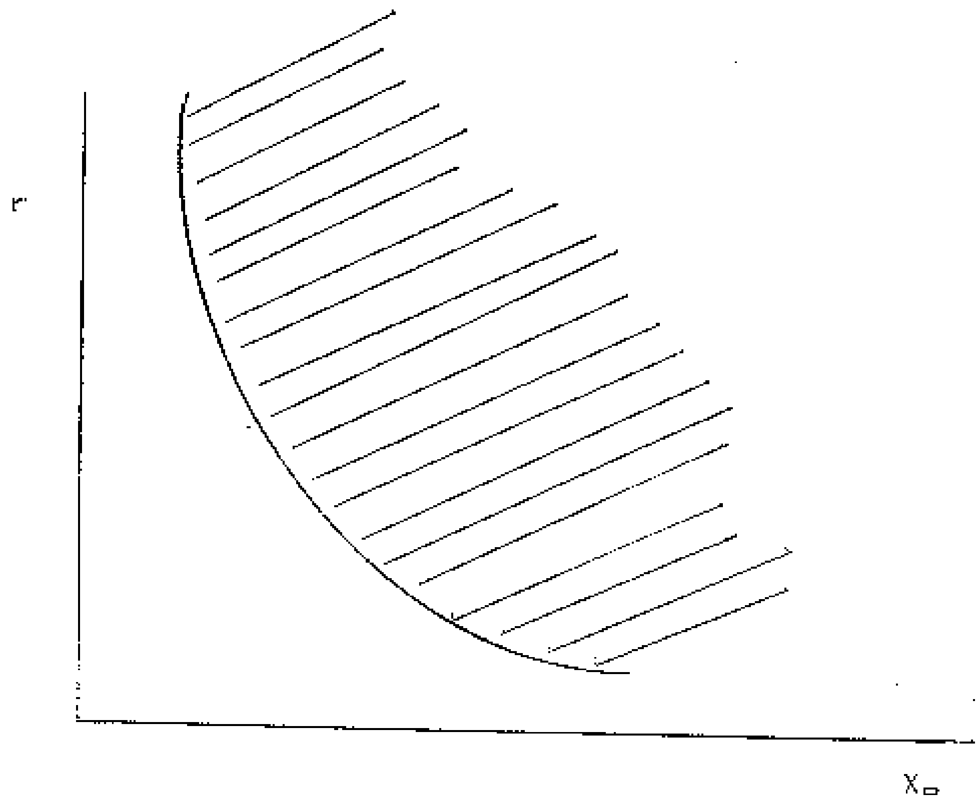


Figure 7. The influence of X_o on r



4. Conclusion

The results of the above model indicate that both the initial level of environmental quality as well as the rate of time preference are significant factors in determining the optimal choice between sustainable and unsustainable growth. For example, if technical condition $h_{cx} < 0$ is satisfied, with a low initial level of environmental quality and a high rate of social discount, environmentally unsustainable economic growth may be an optimal strategy as the benefits of increased consumption occur in the present whereas environmental degradation and collapse is a future problem. Moreover, the initial level of environmental quality influences choices of discount rates, so that a historically lower initial level of environmental quality leads to a high rate of discount and vice versa.

In other words, a low initial level of environmental quality forces resource users to discount the future heavily. That is, poor people faced with marginal environmental conditions have no choice but to opt for immediate economic benefits at the expense of the long-run sustainability of their livelihoods. This particularly holds for the marginal lands of the Third World, which are areas characterized not only by lower quality and productivity but also by their greater instability, especially as regards to micro-climatic, agro-ecological and soil conditions.[17] Thus if economic development is to offer the resource-poor the opportunity of sustainable and secure livelihoods, then sustainable resource management must become a primary development goal.

For example, one of the consequences of deforestation and the depletion of fuelwood supplies is that it forces poor households to divert dung for use as fuel rather than for fertilizer. The `present value' of the dung as fuel is higher than its value as a soil nutrient, but "the context is one where there is no choice anyway since there are neither fuel nor fertilizer substitutes to which households can gain access". This behaviour, therefore, is itself "the result of the resource degradation process which compels actions to be taken which imply high discount rates".[18] In other words, the high apparent discount rates are a reflection of the constraints imposed by environmental degradation rather than the desired social choice.

The above analysis also has implications for the incorporation of environmental impacts into cost-benefit analysis of development projects. As this expanded approach inevitably raises issues of intertemporal choice, the interest rate chosen to discount the future may determine whether environmental degradation is `optimal' - as demonstrated formally in the model of this paper. But it does not necessarily follow that manipulating the discount rate is the best approach to incorporating concerns for environmental sustainability in the project analysis.

For example, it is often stressed that the appropriate discount rate should emerge from the project appraisal process.[19] In practice, imperfect capital markets, inconsistent data on the productivity of capital and large variances in domestic borrowing for investment make it difficult to establish an economic accounting rate of interest for developing countries.[20] Introducing environmental considerations further complicates the picture. As Markandya and Pearce observe, natural resources are more likely to be over-exploited at high discount rates than at low ones, whereas low discount rates discriminate against projects with an environmental dimension that have a long gestation period.[21] Given the additional problems posed by environmental risk and irreversible impacts, these authors conclude that it is generally preferable to adjust the project costs and benefit values and adopt additional sustainability criteria than to adjust the discount rate. Alternatively, one could require as a planning criterion that the environmental damages inflicted by a given portfolio of projects must be compensated by the net environmental benefits generated by an additional set of projects.[22]

Thus the fact that the choice of discount rate is not independent of the historically given level of environmental quality - i.e., that the resource degradation process may compel actions that imply high discount rates - does not necessarily mean that choosing a low level of discount rate will automatically make development projects more 'sustainable'.

Notes

1. Earlier versions of the model presented in this paper appeared in Edward B. Barbier, "Sustainable Natural Resource Management as a Factor in International Economic Security", Paper presented at the Center for Economic Policy Research Workshop on Economic Aspects of International Security, London, 18 March 1988 and in Edward B. Barbier, Economics, Natural Resource Scarcity and Development: Conventional and Alternative Views, Earthscan, London, 1989, ch. 8.

2. For example, the wider, highly normative view of sustainable development was endorsed by the World Commission on Environment and Development (WCED), Our Common Future, Oxford University Press, Oxford, 1987, which defines the concept as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". See also Edward B. Barbier, "The Concept of Sustainable Economic Development", Environmental Conservation, Vol. 14 (1987), pp. 101-110. For further discussion of the more `narrow' interpretation of environmentally sustainable development, see Edward B. Barbier, Economics, Natural Resource Scarcity and Development: Conventional and Alternative Views, Earthscan Publications, London, 1989, ch. 9 and David W. Pearce, Edward B. Barbier and Anil Markandya, Sustainable Development; Economics and Environment in the Third World, Edward Elgar, London, forthcoming.

3. David W. Pearce, "The Meaning and Implications of Sustainable Development", Report of a Workshop on Sustainable Development, Economics and the Environment Secretariat, OECD, Paris, 12-13 November 1987. Members of the Workshop were Edward B. Barbier, Peter Nijkamp, David W. Pearce, R. Kerry Turner and the Secretariat. The term `economic development' is used here to imply structural change in the economy and society, and can be conventionally defined as the "process whereby the real per capita income of a country increases over a long period of time - subject to the stipulations that the number below an `absolute' poverty line does not increase, and that the distribution of income does not become more unequal". See Gerald M. Meier, Leading Issues in Economic Development, 3rd ed., Oxford University Press, New York, 1976.

4. Examples where this may be the case include extensive deforestation of tropical forests, such as is occuring in Amazonia, upper watershed degradation through inappropriate upland farming and even the global warming induced by greenhouse gases. For further discussion of the economic aspects of these `system breakdowns' see Edward B. Barbier, Economics, Natual Resource Scarcity and Development, op. cit., chs 7 and 8.

5. See, in particular, Pearce, "Foundations", op. cit.; David W. Pearce, "The Limits of Cost-Benefit Analysis as a Guide to Environmental Policy", Kyklos, Vol. 29 (1976), pp. 97-111; David W. Pearce, "Optimal Prices for Sustainable Development", in D.

Collard, D.W. Pearce and D. Ulph eds., Economic Growth and Sustainable Environments, Macmillan, London, 1988; Talbot Page, Conservation and Economic Efficiency: An Approach to Materials Policy, Johns Hopkins University Press, Baltimore, 1977; and Edward B. Barbier, "Alternative Approaches to Economic-Environmental Interactions", Paper presented at the 13th Annual Eastern Economic Association Conference, Washington, DC, March 5-7, 1987. See also the discussion and references cited in Pearce, Barbier and Markandya, op. cit. and in Herman E. Daly, "The Economic Growth Debate: What Some Economists Have Learned But Many Have Not", Journal of Environmental Economics and Management, Vol. 14 (1987), pp. 323-336. Finally, see the interpretation placed on Hartwick's rule by Robert M. Solow, "On the Intergenerational Allocation of Natural Resources", Scandinavian Journal of Economics Vol. 88 (1986), pp. 141-9, which suggests that a policy of investing resource rents in reproducible capital implies that some appropriately defined stock (natural plus reproducible) is being maintained intact, and that consumption can be regarded as the `interest' on that stock.

6. These conditions ensure that the environmental degradation resulting from the failure to observe the biophysical constraints poses a threat to the long-run sustainability of the economic process; alternatively, the violation of any one of these conditions would alleviate this threat. This follows from an extension of the analysis presented in Partha Dasgupta and Geoffrey Heal, Economic Theory and Exhaustible Resources, Cambridge University Press, 1979, ch.7. For example, if the three important economic functions of the environment are broadly considered to be the production of useful material and energy inputs, E_1, the assimilation of waste, E_2, and the provision of human, ecological and life-supporting services, E_3, then each of these E_i functions is essential if in its absence feasible consumption must necessarily decline to zero in the long run. On the other hand, if reproducible capital, or a labor-capital composite, can be sufficiently substituted for each E_i, then it is no longer essential. Equally, even in the absence of such substitution possibilities, if each E_i could be augmented by a constant positive rate of technical progress, the loss of that function could be managed to ensure that its technically enhanced services are bounded away from zero. Note also that, if perfect substitution of reproducible for natural capital is not possible, the policy of investing resource rents in reproducible capital as suggested by Solow op. cit. may no longer generate a constant consumption stream.

7. See Edward B. Barbier, "Alternative Approaches", op. cit.; Robert A. Becker, "Intergenerational Equity: The Capital-Environment Trade-Off", Journal of Environmental Economics and Management, Vol. 9 (1982), pp. 165-85; Karl-Goran Maler, Environmental Economics: A Theoretical Inquiry, Johns Hopkins University Press, Baltimore, Maryland, 1974; and Neil Vousden, "Basic Theoretical Issues of Resource Depletion", Journal of Economic Theory, Vol. 6 (1973), pp. 126-43.

8. As W is total waste from the economic process and thus comprises waste from exhaustible resource extraction, from renewable resource harvesting and production and consumption, it may appear that equation (1) is double counting. But equation (1) is not accounting for the flow of material through the economic system but for the total impact on the environment, i.e the 'composite' resource base, of the waste generation and resource depletion created by the economic system. For example, a forest might be depleted faster than its rate of regeneration, whereas the total waste generated by the harvesting plus production and consumption of the wood products may not exceed the assimilative capacity of the environment. Looking at the total impact on the environment of this economic activity therefore requires accounting for both the impact of the total waste generation - which is negligible in this example - and the impact of the harvesting - which is significant.

9. Note also that the condition $R + E \leq G$ allows for steady substitution of renewables for exhaustible resources as stocks of the latter allow and increase in relative scarcity. Thus, as argued by Pearce, "Foundations of an Ecological Economics", op. cit., if the resource base is viewed as a composite of renewables and renewables, if users are indifferent between which is used, and if the renewable resource use rate should never exceed the regeneration rate, then exhaustibles can safely be diminished by current generations. As a result, the composite stock of resources can be maintained across generations, even though in physical terms current extractions of non-renewables will reduce the stock available to future generations.

10. Following Becker, op. cit. and Maler, op. cit., it is assumed that environmental quality - our X variable - is measured by a stock of environmental goods that yield a flow of services proportional to that stock in each time period. However, Becker defines this stock variable as 'the differences between the level of pollution for which life ceases and the current level of pollution.' Similarly, Maler considers only the quality and flow of waste residuals and recycling to have an impact on environmental quality in his intertemporal models. Here it is assumed that environmental quality may be affected not only by net waste generation but also by net resource depletion, as both of these may contribute to environmental degradation if biophysical limits are exceeded (See equation (1)). This implies a fairly broad, but perhaps more realistic, concept of the "stock" of environmental assets. 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.

11. See, for example, R.C. d'Argè and K.C. Kogiku, "Economic Growth and the Environment", Review of Economic Studies, Vol. 40 (1973), pp. 61-78; A.V. Kneese, R.U. Ayres and R.C. d'Arge, Economics and the Environment: A Material Balances Approach,

Johns Hopkins University Press, Baltimore, 1970; Maler, op. cit.; and Peter A. Victor, Pollution: Economics and the Environment, Allen & Unwin, London, 1972.

12. See Bruce A. Forster, "Optimal Consumption Planning in a Polluted Environment", Economic Record, Vol. 49 (1973), pp. 534-45; Bruce A. Forster, "Optimal Pollution Control with a Nonconstant Exponential Rate of Decay", Journal of Environmental Economics and Management, Vol. 2 (1975), pp. 1-6; and Bruce A. Forster, "Consumption-Pollution Trade-Offs", in J.D. Pritchard and S.J. Turnovsky, eds. Applications of Control Theory to Economic Analysis, North-Holland, Amsterdam, 1977.

13. See, for example, Colin W. Clark, Mathematical Bioeconomics: The Optimal Management of Renewable Resources, John Wiley, New York, 1976 and Partha Dasgupta, The Control of Resources, Basil Blackwell, Oxford, 1982.

14. See Gordon R. Conway, "The Properties of Agroecosystems", Agricultural Systems, Vol. 24 (1987), pp. 95-117.

15. See, for example, the models by Becker, op. cit.; Clark, op. cit.; Dasgupta, op. cit.; and Forster, "Optimal Control", op. cit.

16. Edward B. Barbier, The Economics of Farm-Level Adoption of Soil Conservation in the Uplands of Java, Environment Department Working Paper No. 11, World Bank, Washington DC, October 1988.

17. See, for example, Edward B. Barbier, "Sustainable Agricultural and the Resource Poor: Policy Issues and Options", LEEC Paper 88-02, London Environmental Economics Centre, October 1988; Robert Chambers, "Sustainable Livelihoods, Environment and Development: putting poor people first", Discussion Paper 240, Institute of Development Studies, University of Sussex, Brighton, England, December 1987; Gordon R. Conway and Edward B. Barbier, "After the Green Revolution: Sustainable and Equitable Agricultural Development", Futures, Vol. 20 (1988), pp. 651-70; and Gordon R. Conway, Ibrahim Manwan and David S. McCauley, "The Development of Marginal Lands in the Tropics" Nature, Vol. 304 (1983), p. 912.

18. David W. Pearce, "The Economics of Natural Resource Degradation in Developing Countries", in R. Kerry Turner (ed.) Sustainable Environmental Management: Principles and Practices, Bellhaven Press, London and Westview Press, Boulder, Colorado, 1988.

19. See UNIDO, Guidelines for Project Evaluation, United Nations, New York, 1972.

20. David A. Phillips, "Pitfalls in Estimating Social Discount Rates: A Case Study", Project Appraisal, Vol. 1 (1986), pp. 15-20.

21. Anil Markandya and David W. Pearce, Environmental Considerations and the Choice of the Discount Rate, Environment Department Working Paper No. 3, World Bank, Washington DC, May 1988.

22. David W. Pearce, Edward B. Barbier and Anil Markandya, "Sustainable Development and Cost-Benefit Analysis", LEEC Paper 88-03, London Environmental Economics Centre, November 1988.

The London Environmental Economics Centre (LEEC) is now known as the Environmental Economics Programme, at the International Institute for Environment and Development. The former name dates from 1987 when the Centre was established by IIED and the Economics Department of University College, London.

Today, all environmental economics staff and research projects are based at IIED where the Programme has become a core area of Institute activity.

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