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Sustainable Development and Complex Ecosystems:

An Economist's View

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Abstract

The paper surveys economic aspects of sustainability and the use of complex ecological systems. In a first step, an economist's view of the concept of sustainability is presented. Then, a simple model of the economic use of a dynamic ecological system is discussed. It is shown how economically optimal trajectories look like, in which circumstances it may be optimal to destroy the ecosystem, and which problems arise if this ecosystem is a common-property resource. Extensions of the model that add complexity and uncertainty are referred to briefly. Finally, some economic concepts to determine the value of ecosystems are presented.

1 Introduction

Human society and its economic system are embedded into the natural environment. Economists for a long time neglected this and regarded the availability of nature's services to society as granted and as being outside their area of research. This has changed during the last two decades and economists came up with solutions such as environmental taxes, but their understanding of ecological systems is still rather limited. Ecologists, in contrast, tended to disregard the impact of the economic and social systems on nature and when they started to look at the human impact on ecological systems, they usually did this in a descriptive manner. They often lack the knowledge of the functioning of economic systems and their policy instruments and, therefore, cannot address the normative aspects of the problem. This paper is an attempt to indicate some issues where economists and ecologists could learn from each other and where a process of cross-fertilisation could yield important results. Since I am an economist myself, I will start from an economic point of view. But I will incorporate elements of population biology to model the dynamics of ecological systems - or what an economist thinks the dynamics of an ecological system are.

The paper starts with a brief discussion of the concept of sustainability. Then I move to a simple dynamic model of interactions between the economic and ecological systems. Some extensions of the model that are useful to deal with complexity and uncertainty will be discussed. Afterwards, I will look at the problem of evaluating environmental resources. Some final remarks conclude the paper.

2 The Concept of Sustainable Development

Sustainable development has become a catchword in the environmental policy debate. It has been coined in the Brundtland report, WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT (1987). For a definition, see p. 43 of the report:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

This definition is rather general and vague and, therefore, hardly applicable to real-world issues. Thus, economists have tried to operationalise the concept. See PEZZEY (1992) and REID (1995) for surveys.

The development possibilities of a society or of a generation of society are determined by the initial capital endowment it has inherited from the past. This capital stock consists basically of three different components: natural capital (exhaustible and renewable resources, biodiversity etc.), man-made physical capital (production equipment, durable consumer goods), and knowledge capital (technological knowledge, knowledge about nature, and knowledge about society and its institutions).

There are two major controversies in the sustainability debate. The first one concerns the substitutability of these three kinds of capital for each other. Technocrats and many mainstream neoclassical economists argue that there are good substitution possibilities. This implies that the degradation of natural capital is no problem as long as enough man-made physical and knowledge capital are accumulated and passed over to

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the next generation. This view is challenged by many natural scientists and heterodox economists who are less optimistic. They argue that substitutability is limited in the long run, e.g. by thermodynamic thresholds and that, therefore, conservationism is the correct strategy of resource management. This dispute is unlikely to be resolved in the near future. Nonetheless, irrespective of which view of substitution possibilities turns out to be correct, the concept a multidimensional capital stock can be very useful for the assessment of sustainable development. In a recent study, World Bank economists looked at the growth of aggregate capital stocks in various countries and came to the alarming conclusion that some countries indeed erode their basis of future development in order to satisfy the needs of the present generation.

The other controversy is about intergenerational equity. How should the interests of future generations be taken into account? Is a positive discount rate justifiable and if it is, how large should the discount rate be? This is an ethical question and cannot be answered on a scientifc basis. In the model I will introduce in the next section future benefits will be discounted, but no assumption about the size of the dsicount rate will be made. It may be very small, e.g. less than one percent.

3 The Use of Simple and Complex Ecological Systems

How can the interactions of the ecological and economic systems be modelled? The modelling framework is inherently dynamic. One reason is the intertemporal trade-off between the welfare of the present and that of future generations. The second reason is the dynamic nature of ecological systems. An ecological systems reacts to disturbances but the adjustment speed is finite and depends on the state of the system. Ecologists refer to this as resilience (HOLLING 1973) and economists usually talk about assimilative capacity. Another feature of ecosystems is their complexity. They usually consist of many (often thousands, sometimes millions) of interacting species. I will start with a single-species model. This may be taken literally but it may also be interpreted as an aggregation of a multidimensional eco-system. Human society extracts resources and uses them for economic purposes. In my model, the extraction rate simply reduces the resource base, but the generalisation to more general, non-linear, modes of interaction between economy and ecology is straightforward. I neglect evolutionary aspects of both the ecological and economic systems. Technological progress in the economic system and evolutionary change in the ecological system are disregarded.

3.1 A simple reference model

Let there be n identical units (fishing vessels exploiting a fishery or countries using a common resource base) using a renewable resource whose stock at time t is $R(t)$. The initial resource stock, R^0, is exogenously given and there is a regeneration function $g(R(t))$ having the usual shape. There may be an interval $(0, R^l)$ in which $g(.)$ is negative indicating the existence of a minimum stock necessary for the survival of the species or the ecosystem. In the interval (R^l,R^u), $R^l<R^u$ the $g(.)$ function is concave and non-negative. It becomes zero for R^u, the maximum stock of the species that can be sustained by the environment it is living in. If $R(t)$ is interpreted as the ecosystem as a whole, R^u denotes its original state in the absence of human activities. Let the extraction rate at time t be $x(t)$ for each unit. A dot above a variable denoting the time derivative of a variable, the change in the resource stock can be written as:

(1) $$\dot{R}(t) = g(R(t)) - nx(t).$$

Let there be a social planner maximising the representative unit's utility. The utility function, $u(.,.)$ depends on the extraction rate and on the resource stock. Moreover, it is assumed to be increasing in its arguments and strictly concave. The impact of the resource stock can be interpreted as that of environmental quality on human well-being. Under the assumption of intertemporal separability, the utility is the present value of all future utility flows. Let the time horizon be infinite and let the discount rate be $r>0$. Then the social planner's objective is to maximise

(2) $$\int_0^\infty e^{-rt} u[x(t), R(t)]dt$$

subject to (1) and to the transversality conditions $R(0) = R^0$ and $\lim_{t\to\infty} R(t) \geq 0$ The solution of this problem is a straightforward one in economics. See CLARK (1990, ch. 6) for a similar model having the same algebraic structure. There is a long-run equilibrium characterised by

$$(3) \qquad g' + n\frac{u_R}{u_x} = r$$

where the prime denotes the derivative of a function with respect to its argument, subscripts denote partial derivatives and where the arguments of the functions have been omitted for convenience. The economic interpretation of this condition is the following one. The resource is a store of value, i.e., an asset. On the right-hand side, there is the discount rate which can be interpreted as the rate of return to an alternative asset. On the left-hand side, there is the marginal rate of reproduction of the resource plus a term measuring the marginal benefit to be derived from the existence of the resource. These two terms represent the rate of return to the resource as an asset. Thus, eq. (3) is an indifference condition indicating that all assets should yield the same marginal rate of return. The equilibrium is stable in the saddle-point sense and the saddle path is positively sloped. See Figure 1. The larger u_R , the larger is the equilibrium resource stock. It may be larger than the stock providing the maximum sustainable yield (MSY). If u_R is small, if the rate of regeneration is small and if the discount rate is large, then the resource stock is likely to be smaller than the MSY stock. It may even be optimal to exhaust the resource in cases where an equilibrium with a positive value of $x(t)$ does not exist.

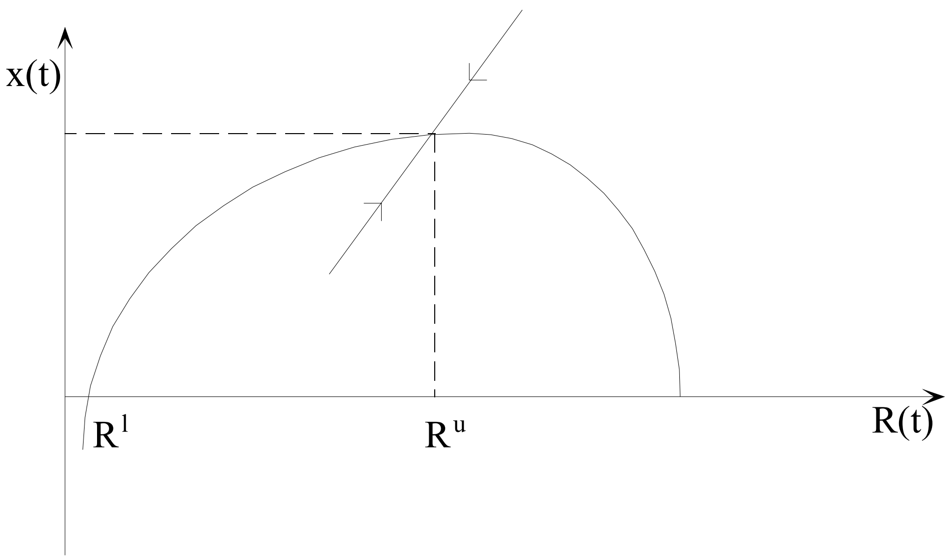

Figure 1: Optimal Use of a Renewable Resource

3.2 Uncoordinated Use of the Resource

The reference scenario shows a social planner's solution to the renewable-resource problem. In many real-world cases, however, this is rather unrealistic. Property rights to resources are often incompletely defined, regulating entities are missing. Examples are international fisheries or international environmental media like rivers, lakes, seas, and the atmosphere, that do not respect national boundaries. In these cases, each of the *n* units solves its own optimisation problem. Let us look at simple (open-loop) Nash equilibrium where each player optimises his/her own choice of *x(t)* for given choices of the other units.[2] For player *i*, the state constraint turns out to be

(4) $$\dot{R}(t) = g(R(t)) - x^i(t) - \sum_{j \neq i} x^j(t).$$

The Nash equilibrium is based on full information, i.e., each player seeks the optimal response to the optimal strategies chosen by the other players. This explains

2 For more complex but also more realistic models of non-cooperative resource exploitation see LEVHARI/MIRMAN (1980) and DOCKNER/ FEICHTINGER/MEHLMANN (1989).

why, ex post, all players will do the same thing. Thus, we can drop the superscripts and the long-run equilibrium turns out to be

(5) $$g' + \frac{u_R}{u_x} = r$$

This equilibrium again is saddle-point stable (if it exists). Compared to eq. (3), the term *n* has vanished. This implies that the equilibrium resource stock is smaller than in the reference scenario. It is also possible that a resource which should be preserved from a social planner's point of view is exhausted within finite time by uncoordinated users. This is HARDIN'S (1968) "Tragedy of the Commons". See also GORDON (1954) for an early treatment of over-fishing problems and LEVHARI/ MIRMAN (1980) and DOCKNER/FEICHTINGER/MEHLMANN (1989) for modern approaches.

A central planner would be useful for the solution of the over-exploitation problem, but in reality this is unlikely to be a good policy suggestion. Rather would one like to use, incentive-based resource-conservation schemes, e.g. environmental tax rates. A tax rate which makes non-cooperative users of the resource behave as if they cooperated is given by:

(6) $$q = \frac{n-1}{n} u_x .$$

u_x is the marginal utility derived from the use of an additional unit of the resource. Besides the individual under consideration, *n-1* other individuals can benefit. Each individual has to pay one *nth* of this amount. If the utility function is additively separable in its arguments, the tax rate is a declining function of the resource stock along the optimal path. This means, the larger the initial resource stock, the smaller is the initial environmental tax rate.

3.3 Capital as a Substitute for the Resource

Let us now turn to the sustainability problem and introduce man-made capital. The idea is that the accumulation of capital may reduce some of the problems that are due to the scarcity of natural capital. Man-made capital, *K(t)* enters the production process as a means to save resources. The other factor is the quantity of the resource extracted, *x(t).* Let the (net) production function, *f(.,.),* be increasing in its arguments. Let the second derivatives be negative and the cross derivative be positive. The resource-extraction process is modelled by equation (3) again. Capital accumulation is described by

$$(6) \qquad \dot{K}(t) = f[K(t), x(t)] - c(t)$$

with given initial capital stock and a non-negativity constraint on the long-run capital stock. The objective function then is

$$(8) \qquad \int_0^\infty e^{-rt}\ u[c(t), R(t)]dt$$

where $x(t)$ has been substituted for by $c(t)$.

The control variables are $x(t)$ and $c(t)$. The problem can be solved by application of Pontryagin's maximum principle. The long-run equilibrium is characterised by $f_K = r$ as a condition for the equilibrium capital stock and

$$(9) \qquad g' = r - n\frac{u_R}{u_c f_x}$$

as the condition for the equilibrium resource stock. Eq. (9) is similar to eq. (3). The difference is that in the reference model the harvested resource, $x(t)$, enters the utility function directly, whereas in the modified model a production process is necessary to transform natural resources into consumption from which utility can be derived. f_X is the additional consumable output obtained by a marginal increase in $x(t)$ and u_C is the utility derived from consuming this output. Thus, $u_C\, f_X$ and u_X represent basically the same thing. Thus, the long-run equilibrium in a model with man-made capital is not much different from the equilibrium in a model without such capital. However, this equilibrium is not necessarily stable in the saddle-point sense. There are two-state variables in the model and, therefore, the optimum trajectory is a two-dimensional manifold in a four-dimensional phase space. It has been established for models with a similar structure that this manifold can be unstable. Cyclical behaviour is possible. See

RAUSCHER (1990) for an example. Although a different problem is discussed in that model, the algebraic structure is similar to the one presented here. FEICHTINGER/ NOVAK (1992) have shown that limit cycles are possible, i.e., it can be optimal to have cyclical extraction and capital accumulation strategies that neither approach an equilibrium nor the boundaries of the admissible part of the phase space. Although this behaviour resembles cyclical trajectories in some predator-prey system known from population biology, its explanation is a different one here. In biological systems, the cycles originate from the adaptive (and thus myopic) behaviour of the species. In the economy-ecology model, these paths are chosen by a social planner endowed with perfect foresight.

As before, the resource stock may be driven to exhaustion if r is large and g' and u_R are small. This is possible for the case of a social planner and more likely in the case of uncoordinated strategies. In this model, however, it is possible that the accumulation of man-made capital offsets the problem of diminishing natural capital. As has been argued before, this depends decisively on the elasticity of substitution between man-made and natural capital. See DASGUPTA/HEAL (1974, 1979) for an algebraic treatment of this question in the framework of exhaustible-resources models.

3.4 Multi-species problems

Ecological complexity can be modelled by introducing additional species. These species, or more generally: components of ecological systems may interact in a very complex fashion. STRÖBELE/WACKER (1995) have tried to model an optimum-resource-use problem for the still relatively simple case of two interacting species. A general solution turned out to be impossible. Systems that can be described rather easily by merely two differential equations turn out to be close to intractable when optimal harvesting trajectories are sought. To illustrate this, consider an extended version of the reference model where R and x are vectors with m components. The dynamics of the system are again described by equation (1), but now all variables and functions in this equation are vectors. Such a system may possess multiple equilibria some of which are locally stable. This may lead to issues of irreversibility and path dependence. The simplest case of irreversibility is that where some species are extinct. Path dependence or hysteresis is a phenomenon occurring in multi-equilibrium dynamic systems. A temporary disturbance of the system, say a human intervention into an eco-system may change the system's trajectory such that it approaches another equilibrium. Since this equilibrium is locally stable, the removal of the disturbance does not suffice to re-establish the old equilibrium.

The optimising procedure results in an equilibrium which is characterised by $\dot{R} = 0$ and

$$(10) \qquad (rI - g_R)u_x = nu_R$$

where I is the unit matrix and g_R is now a matrix as well. There are 2n equations and the problem to solve this equation analytically is intractable. The comparative-static results with respect to r and n are ambiguous. Thus, it is not a priori clear whether or not an reduction in the discount rate or a move from uncoordinated to coordinated resource use drive the resource stocks up. Some resource stocks may reduced if a social planner enters the arena. Moreover, the optimal paths are not generally saddle-point stable. Unstable solutions and limit cycles are possible. Path dependence is possible here. E.g. after a period of uncoordinated resource exploitation, it is not always desirable for a benevolent social planner to restore the long-run equilibrium which would have been optimal had there been coordinated extraction policies from the beginning.

3.5 Incomplete Knowledge

The multi-species version of the model is probably much too disaggregated, for the information necessary to specify the functions of such a system may never be available. Thus, simplified models may be justified on these grounds, but one should take into account the uncertainty originating from the lack of knowledge about the true ecological interdependencies. This is done here by assuming that the dynamics of the ecological system in the one-variable case can be described by a Wiener process, i.e., there is a stochastic influence in the state equation. Then:

(11) $dR(t) = g[R(t)]dt - nx(t)dt + s[x(t), R(t)]dz$

where *dz* is a normally distributed random variable with zero mean and variance *dt*. The stochastic component is the more important, the larger *s* is. The variance of *dR*(*t*)*dt* is increasing in *s* and *s* itself may be a function of the resource stock and the extraction rate. The objective is to maximise the expected present value of future utility:

(12) $E\left[\int_0^\infty e^{-rt} u[x(t), R(t)]dt\right]$

The problem can be solved by means of Pontryagin's Maximum Principle (see BISMUT 1975) or by application of Bellman's Principle of Optimality (see FEICHTINGER/HARTL 1986, ch. A.8). Using the Priciple of Optimality one can derive a function which maps the stock of resources on the optimum extraction rate in any moment of time - provided that the model is simple enough. Unfortunately, this model is not simple and cannot be solved explicitly. One of the steps towards the solution is an implicit second-order differential equation. Thus, I use BISMUT'S method. One can derive a long-run equilibrium where the expected resource stock and the expected extraction rate are both constant. It is characterised by

(13) $g' = r - n \dfrac{u_R - ps_R}{u_x - ps_x}$.

π is positive and can be interpreted as the cost of risk. In principle π can be determined explicitly, provided that the model is simple enough. This proviso does not apply here. The interpretation of this equation is straightforward. If a large resource stock increases the stochastic component of resource regeneration, then the long-run expected stock should be smaller than in the deterministic case. However, it is probably more realistic to assume the converse, i.e. that an eco-system that has undergone substantial change due to human intervention is less resilient and more easily affected by exogenous variables. If the stochastic component is an increasing function of the extraction rate or, more generally speaking, of the degree of human intervention into the eco-system, then the long-run stock should be larger than in the deterministic case. The explanation for these results is the risk aversion which is implicit in the utility function. Risk-averse individuals and societies will always avoid risky activities to some extent.

4 Evaluation of Ecosystems

The optimal policies derided in this paper are of a rather general and abstract nature. A long-run equilibrium is identified and it is shown that the optimum path is a positively sloped saddle path in the simple models. Such results are useful because they deepen our understanding of the nature of the problem at hand. However, they are much too abstract to serve as a policy advice. What should be done is to specify the model, i.e., to determine the shapes and parameters of the functions that are relevant in the real world. Two main problem areas can be identified here. The first one is our limited knowledge on the functioning of eco-systems. My impression as a non-expert is that some insights are gained only after irreversible changes have been made. In this case, stochastic optimisation may help to capture our lack of knowledge. The second problem area is that of evaluation. Ecological systems are usually common-property resources with ill-defined property rights. Thus, there exist no market prices which contain information about expected future benefits from the conservation of these resources and about their non-use value, e.g. utility derived by people who know that there are still white rhinos, blue whales and other rare species "out there". How can these things be determined?

What is relatively easy to determine is the commercial value of resources in their contemporary uses. For instance, it will be possible to compute the economic loss caused by overfishing. Matters are different when problems like biodiversity loss in tropical rain-forests and environmental pollution of air and water are concerned. Economists use basically three methods to come to results here:[3]

Contingent valuation. One can simply ask people how much they are willing to pay to conserve certain eco-systems or habitats. Of course, this method is problematic in many respects, including design of the questionnaire, framing of the questions, selection of the sample, information of the interviewed people and biased responses due to the practical irrelevance of the reported willingness to pay.

Hedonic pricing. The idea is to look at the market prices of goods whose value is decisively influenced by environmental variables. An example are house prices, which do not only depend on the properties of the house but also on air and noise pollution and on the properties of the neighbourhood. The approach uses multi-variate regression analysis. The result is a measure of observed willingness to pay (instead of hypothetical willingness to pay as in the case of contingent valuation). Hedonic pricing is useful for some environmental problems but not for all of them. An example is biodiversity loss, which has an rather weak and indirect impact on the prices of marketable commodities.

Travel cost method. People spend money and time to enjoy nature. Both can measured and be used to determine the value of natural resources, e.g. a national park. Again the basis of measurement is the observed rather than the hypothetical willingness to pay. However, this approach is rather limited since it only measures a part of the value of an environmental resource or ecosystem. What is not measured is the value of uses that are not yet known today and the non-use value of the resource.

The conclusion is that there is no completely satisfactory method to determine the value of common-property environmental and ecological resources. We rely on what is available and in spite of their limitations all these methods have in many practical applications proved to be useful to at least approximate the value of environmental and ecosystem resources.

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3 See BRADEN/KOLSTAD (1991) and JOHANSSON (1987) for comprehensive surveys of the achievements in the measurement of environmental damages and benefits.

5 Final Remarks

The paper has shed some light on the problems that arise when solutions to the management of complex ecological systems are sought. Although we have some ideas of what should be done, an exact and reliable analysis of the costs and benefits of environmental-policy measures is often not possible since the underlying information is not available. But it is not the lack of knowledge that explains the deficiencies in the utilisation of environmental resources. Many ecological systems are still used as open-access common-property resources. The uncoordinated use and non-cooperative behaviour of the users lead to overexploitation. This problem is of particular severity in the case where different sovereign jurisdictions have access to a resource. International cooperation in environmental issues is a necessary (albeit unfortunately not sufficient) measure to cope with these problems.

References

BISMUT, J.-M., (1975), Growth and Optimal Allocation of Risks, *Journal of Economic Theory* 10, 239-257.

BRADEN, J.B., C.D. Kolstad, eds., (1991), *Measuring the Demand for Environmental Quality*, Amsterdam: North-Holland.

CLARK, C.W., (1990), *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, 2nd ed., New York: Wiley.

DASGUPTA, P., G. M. HEAL, (1974), The Optimal Depletion of Exhaustible Resources, *Review of Economic Studies (Symposium)*, 3-29.

DASGUPTA, P., G. M. HEAL, (1979), *Economic Theory and Exhaustible Resources*, Cambridge: Nisbet.

DOCKNER, E., G. FEICHTINGER, A. MEHLMANN, (1989), Noncooperative Solutions for a Differential Game Model of a Fishery, *Journal of Economic Dynamics and Control* 13, 1-20.

FEICHTINGER, G., R. HARTL, (1986), *Optimale Kontrolle ökonomischer Prozesse: Anwendungen des Maximumprinzips in den Wirtschaftswissenschaften*, Berlin: de Gruyter.

FEICHTINGER, G., A. NOVAK, (1991), A Note on the Use of Environmental Resources by an Indebted Country, *Journal of Institutional and Theoretical Economics* 147, 547-555.

GORDON, H.S., (1954), The Economic Theory of a Common Property Resource: The Fishery, *Journal of Political Economy* 80, 1031-1038.

HARDIN, G., (1968), The Tragedy of the Commons, *Science* 162, 1243-1248.

HOLLING, C.S., (1973), Resilience and the Stability of Ecological Systems, *Annual Review of Ecology and Systematics* 4, 1-24.

JOHANSSON, P.-O., (1987), *Economic Theory and Measurement of Environmental Benefits,*Cambridge: Cambridge University Press.

LEVHARI, D., L.J. MIRMAN, (1980), The Great Fish War: An Example Using a Dynamic Cournot-Nash Solution, *Bell Journal of Economics* 11, 322-344.

PEZZEY, J., (1992), *Sustainable Development Concepts: An Economic Analysis*, Washington, DC: World Bank.

RAUSCHER, M., (1990), The Optimal Use of Environmental Resources by an Indebted Country, *Journal of Institutional and Theoretical Economics* 146, 500-517.

REID, D. (1995), *Sustainable Development: An Introductory Guide*, London: Earthscan.

STRÖBELE, W., H. WACKER, (1995), The Economics of Harvesting Predator-Prey Systems, *Journal of Economics* 61, 65-81.

WCED, (1987), *Our Common Future*, Oxford: Oxford University Press.