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Development, ecological resources and their management: A study of complex dynamic systems☆

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Abstract

Human well-being depends to a large extent on services provided by ecological systems. In poor countries, this dependence is more transparent than in industrialised countries where the dependence is more indirect. Effective management of these systems requires a good understanding of their properties and in particular a knowledge of the dynamics of the systems. In the article, the dynamics of one 'simple' system is analysed economically. The system is a lake and the interaction between the run-off of nutrients into the lake and the growth of either algae (eutrophication in lakes in northern Europe and North America) or water hyacinths (in lakes in southern and eastern Africa) is studied. It turns out that the dynamics exhibit bifurcation points so that there are two

☆ This article is based on truly collective and interdisciplinary research that has been and still is going on in a 'Theory group on economics of non-linear dynamic systems'. Members of the group are William Brock, University of Wisconsin, Partha Dasgupta, University of Cambridge, Karl-Göran Mäler, Stockholm School of Economics, Charles Perrings, University of York, Marten Scheffer, Agriculture University of Wageningen, David Starrett, Stanford University, Brian Walker, CSIRO, Canberra, Anastasos Xepapadeas, University of Crete, Aart de Zeeuw, University of Tilburg. This group has had some memorable meetings and more are to come. Although the content in this article is as much the contributions of the members as it is mine, I resolve them from any responsibility for remaining errors. I would also like to express my gratitude to Carl Folke for past joint work on the issues raised in this article and to 'Buzz' Holling, University of Florida, Gainesville, for his early discoveries of the importance of resilience in ecological systems.

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basins of attraction. If the system flips to one basin and it is regarded desirable to return to the other basin, there will be hysteresis. Assuming that there are different users of the lake, a differential game is constructed that captures the strategic interests of the users. The resulting equilibrium shows first the conventional negative externality that makes the equilibrium different from the optimal use of the lake and a second, stronger, negative externality that will force the system to a different basin of attraction. Finally, we investigate the use of a tax for bringing back the system to a Pareto optimum.

JEL classification: Q25; C73; C69

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1. Introduction

Environmental resources are resources that are renewable but potentially exhaustible.[1] Such resources encompass clean air and water, fisheries, forests, soil, climate and many others. In this article we will focus on a particular kind of environmental resources – ecological systems – and the services they produce.

Ecological services are produced and sustained by ecosystems. They are generated by the continuous interactions between organisms, populations, communities and their physical and chemical environment.[2] Ecosystems are multi-functional in the sense that they provide several ecological functions and services. Many of the ecological functions and services are indispensable, and of fundamental value since they underpin the welfare of human societies. They include all functions, services and resources derived from ecosystems such as supply of drinking water, production and provision of food and other renewable resources, maintenance of a genetic library, soil preservation and generation, recycling of nutrients, flood control, filtering of pollutants and waste assimilation, pollination of crops, operation of the hydrological cycle, and maintenance of the gaseous composition of the atmosphere.

[1] See Dasgupta (1992).

[2] Solar energy is the driving force behind the development of ecosystems, enabling the cyclic use of the materials and compounds required for system organization and maintenance. Ecosystems capture solar energy through photosynthesis by plants and algae. This is necessary for the conversion, recycling, and transfer to other systems of materials and critical chemicals that affect growth and production, i.e. biogeochemical cycling. Energy flow and biogeochemical cycling set an upper limit on the quantity and number of organisms, and on the number of trophic levels that can exist in an ecosystem. This indirectly constrains the biodiversity of the biological community (Holling et al., 1994).

Hence, the natural capital base in itself is an essential factor of production. It produces and sustains goods and services derived from nature that are essential for human welfare. Drawing conclusions on the state and value of the environment by looking only at gross agricultural, fisheries or forestry output without at the same time looking at changes in the state of the natural capital base is a serious mistake. This is particularly important since this factor of production is a dynamic and complex living system consisting of biological communities which interact with the physical and chemical environment, in time and space, and in a non-linear fashion. This implies discontinuities and thresholds in the state of the ecological resource base. Hence, this crucial factor of production, the ecological system itself, is not a fixed stock that generates a flow of renewable resources infinitely or in a linear fashion. The stock is a changing phenomena, evolving through adaptations to changes or fluctuations in the wider environment. It is the self-organizing ability of the ecosystem, or more particularly the buffer capacity or resilience[3] of that self-organization, that determines its capacity to respond to perturbations imposed by exploitation or pollution.

Human simplification of the ecological resource base, through excessive resource extraction, severe land use modifications, environmental deterioration or reductions of biological diversity, not only affects the quantity and qualitity of resources and services produced by ecosystems, but also challenge their resilience. Resilience is the capacity of the system to recover from perturbations, shocks and surprises, its capacity to absorb them. Due to the complexity and non-linearities of the resource base a reduction in resilience is not always easily observable. These dynamic and non-linear aspects of the natural capital needs to be taken into account. The functioning of the system needs to be understood. Otherwise, the ecological support system may loose its resilience, and flip to a totally new one. Avoiding such flips or thresholds refers to the system's carrying capacity. A major ecological importance of biological diversity is its role in preserving ecosystem resilience, thereby remaining within thresholds and carrying capacity.[4] Biological diversity has two major roles in ecosystem development and evolution. First, it provides the units

[3] Resilience of a system has been defined in two very different ways in the ecological literature. The more traditional focuses on resilience in the context of *efficiency* of function, that is resistance to disturbance and speed of return to a near equilibrium steady state (e.g. Pimm, 1991). The definition that is used here is based on Holling (1973, see also Kay, 1991) and focuses on resilience in the context of *existence* of function, that is the amount of disturbance that can be sustained and absorbed before a change in system control or structure occurs. In contrast to the first definition, this one emphasizes conditions far from equilibrium steady state, where instabilities can flip a system into another regime of behaviour (Ludwig et al., 1997).

[4] Carrying capacity is the maximal population size of a given species that an area can support without reducing its ability to support the same species in the future, and is a function of characteristics of both the area and the organisms (Daily and Ehrlich, 1992).

through which energy and material flow, giving the system its functional properties. Second, it provides the system with the resilience to respond to unpredictable surprises.

Carrying capacity is never stable, because of the continuous evolution of systems. Economic policies that apply fixed rules for achieving constant yields, for example fixed carrying capacity of cattle or wildlife, or fixed sustainable yield of fish of wood, lead to ecological systems that increasingly lack resilience. That is, lead to ones that suddenly break down in the face of disturbances that previously could be absorbed (Holling et al., 1995). This is exemplified by grazing of semi-arid grasslands in east and south Africa. Grasslands of semi-arid east and south Africa are periodically pulsed by episodes of intense grazing by large herbivores under natural conditions. This results in a dynamic balance between two functionally different groups of grasses. One group tolerant to grazing and drought, with the capacity to hold soil and water. The other productive in terms of plant biomass and with a competitive advantage over the other group when intensive grazing is absent. In this way, a diversity of grass species is maintained that serves ecological functions of productivity on the one hand and drought protection on the other. Grazing by large herbivores that shift from intense pulses to periods of recovery is a part of the dynamics of the system. However, when fixed management rules are applied, such as the stocking of ranched cattle at a 'sustained' moderate level, the functional diversity is reduced. This is due to a shift from the natural intense pulses of grazing to a more modest but persistent grazing. The modest and persistent grazing supports the competitive advantage of the productive but drought-sensitive grasses over the drought resistant and soil- and water-holding grasses. Thereby diversity narrows to one type of function, drought resistance can no longer be sustained, and the grassland can flip and become dominated and controlled by woody shrubs of low value for grazing. There are many examples of resource and ecosystem management and economic policies that share the same feature of gradual loss of functional diversity, for example in agriculture, fisheries and forest management (e.g. Perrings and Walker, 1995; Holling et al., 1995; Folke and Kautsky, 1992).

The significance and value of the 'infrastructural composition' of the environment and its dynamics has received little attention in economics. This is surprising, since the production capacity of the resource base constitutes the foundation for economic development and human welfare. A challenge is to estimate the stream of benefits forgone as a result of the contraction of the range of environmental conditions in which ecosystems can continue to provide positively valued ecological services. A major difficulty lies in the limitations of commonly used models to consider the non-linear behaviour of the natural capital stock. They insulate the economic system from its environment and ignore the evolutionary tendencies of the resource base, thereby abstracting from the important characteristics of self-organizing systems, i.e. the existence of environmental feedbacks, thresholds and discontinuities (non-convexities). Because of both the evolutionary nature of an ecosystem's response to change in the level of economic stress and the existence of threshold effects, these feedbacks may be largely unpredictable except over ranges of stock sizes in which the ecosystem exhibits local stability. In other words, there are dynamic general equilibrium effects which tend to be ignored (or even not perceived) in the process of aggregating values derived from partial observations of expenditure patterns given some change in the level of ecological resources or services, and which are unpredictable unless the ecosystem stays within the thresholds (Perrings et al., 1995).

Humans all over the world depend on the services generated by ecological systems. It is true for us in the rich industrialized countries as well as for people in poor countries. The difference is that in rich countries, people can shelter themselves from collapses in the resource base by diversifying through trade or by substituting (in the short run) one resource for another.[5] People in poor countries do not have this opportunity.

In poor countries, households are directly much more dependent on the local resource base and a collapse of that resource base means disaster. The situation is exemplified with the following example.

Households along Alaknanda river in northern India spend proportionally their working time on different activities as follows:[6]

Cultivation	30%
Fodder collection	20%
Fuel collection, animal care, grazing	25%
Household chores (cooking)	20%
Other	5%

75% of the time is spent on collecting products from the adjacent ecosystems and 20% on processing the harvest. It shows an extreme dependence on local ecosystems. However, it is probably an underestimate of the dependence on ecological services as it does not reflect all the indirect services provided. Hydrological control, regulation of the microclimate, and waste assimilation do not require working time but are still of importance for the well being of the people living there.

An example of the role of eco-systems to control water flows is given by the fynbos in Cape Province in South Africa. Fynbos consist of several thousand different plants, most of which are endemic in the area. The biodiversity is so rich that compared with its size it has the highest biodiversity in the world. In

[5] These substitution possibilities are discussed in a forthcoming article by P. Dasgupta, S. Levin, J. Lubchenco, and K.-G. Mäler.

[6] Dasgupta and Mäler, 1995 and the references therein.

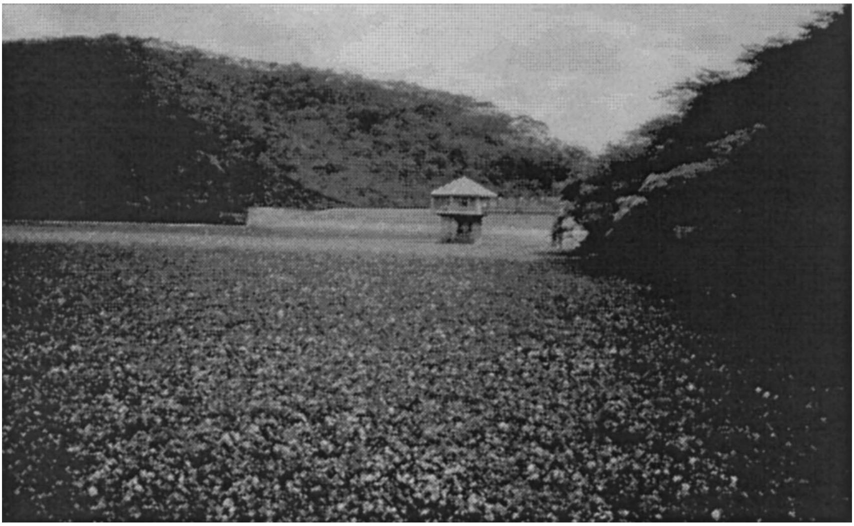

Fig. 1. The dense carpet of water hyacinths on Harare's water reservoir. Photo Nils Kautsky.

fact, the fynbos are regarded as a floral kingdom. However, when Europeans settled in South Africa centuries ago, they brought tree species from Europe with them and these species have taken over some of the land that previously was covered by the fynbos. European tree species do, unfortunately, evaporate much more water than the original fynbos. The result is a water shortage in the province, a shortage that can be mended only by removing the invading species and restore the original ecosystem.[7] Thus, the change of the natural ecosystem did have important effects on the flow of services and in particular on the flow of water.

A last example is the role of the water hyacinths in eastern and southern Africa. The hyacinth comes originally from South America but was introduced in southern Africa some decades ago. Lacking natural enemies, its population exploded and created havoc with many lakes in the region. The dense carpet of hyacinths on the surface of lakes effectively eliminates the use of manual propelled boats and thus makes navigation impossible. Furthermore, fishing, which may have been a major activity in many villages, are much reduced. In addition to that, the dead hyacinths will consume free oxygen in water while decomposing. This reduced level of oxygen will of course affect fish stocks and in general change the conditions for fishing activities further. Finally, the hyacinths will damage water works such as hydro-power plants or dams (Figs. 1 and 2).

[7] See Cowland et al. in Daily (1997). For similar impacts on water flows from changes in vegetation covers see Baskin (1997).

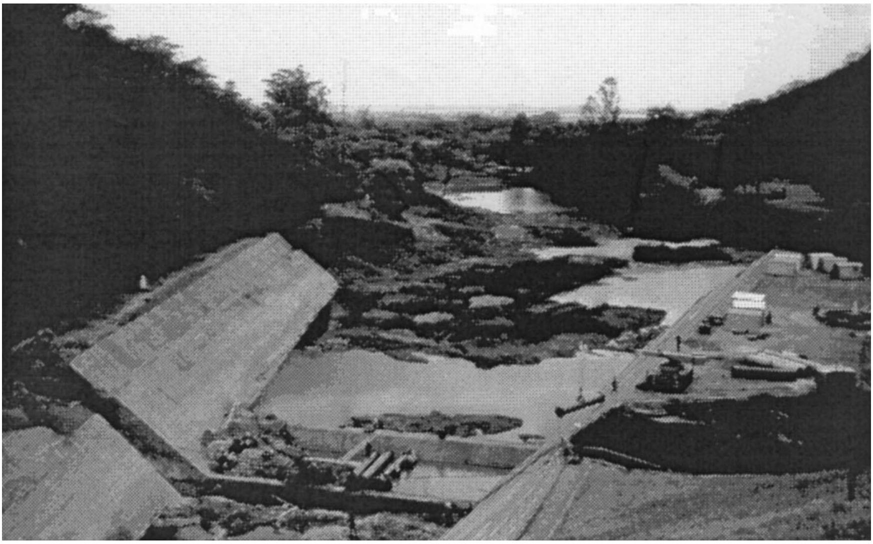

Fig. 2. The destruction of the dam in Harare's water reservoir due to water hyacinths. Photo: Nils Kautsky.

One reason for the success of the water hyacinth in Africa is the lack of natural predators. Today, some insect species have been found that can decimate the carpets of hyacinths. However, as long as the underlying causes for the success is probably the nutrient flows (communication from professor Nils Kautsky). In fact, it seems probable that the hyacinths appear as a result of over fertilization of lakes and that the explosion of the hyacinths resembles the process of eutrophication in lakes in northern Europe and North America.

2. Eutrophication

2.1. Oligotrophic and eutrophic lakes

Ecosystems in lakes depend on the available nutrients. Most often, phosphorous is the limiting nutrient.[8] Phosphorous occur naturally in lakes, but man can often contribute to the flow of nutrients through sewage and runoff of fertilizers used in agriculture. The effect of such flow of phosphorous into a lake is the

[8] The production of biomass depends on the availability of phosphorous and nitrogen and it seems that the production can be described with a Leontief production function. Most often, phosphorous is limiting in lakes and nitrogen is limiting in seas.

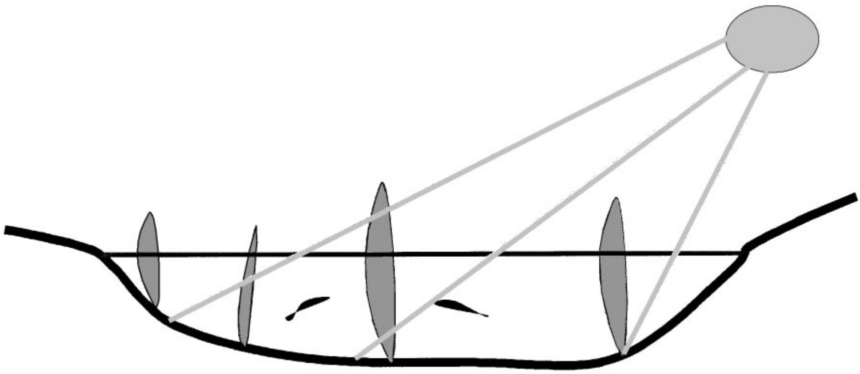

Fig. 3. An oligotrophic lake.

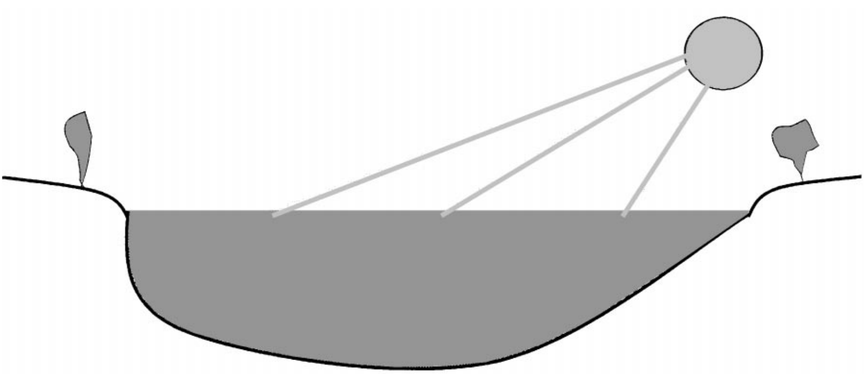

Fig. 4. Eutrophic lake.

growth of algae which can change a clear blue lake with green plants and a particular diversity of fishes to a lake with very little visibility and with hardly any green plants and with a general reduction in fish stocks and in particular a change in the composition of fish stocks.

The original clear blue lake is said to be oligotrophic, that is nutrient poor. The sun shine will reach the bottom which will allow green plants to grow. If we only look at amenity values of lakes, an oligotrophic lake is the ideal for sports or other recreation activities but also for commercial fishing (Fig. 3).

When phosphorous is added to the lake through sewage or runoff from farmland, green algae start to grow. If the process is allowed to continue, the visibility in the water will be substantially reduced and sun light will not be able to penetrate the water. As a result all green plants will eventually disappear. The lake will no longer be suitable for recreation or fishing (Fig. 4).

2.2. The dynamics of shallow lakes

A naive formulation of the dynamics of the eutrophication process might be

$$\frac{dx}{dt} = a - bx,$$

where x is the stock of phosphorous in algae in the lake, a is the runoff of phosphorous into the lake, and b is a constant describing the natural removal of phosphorous from the water (mainly in the form of sedimentation). However, this formulation does not take into account the role of the green plants in controlling the bottom of the lake. When the amount of green plants is reduced, the bottom sediments will be more vulnerable to winds, waves and bottom eating fishes. As a result, sedimented phosphorous will be released into the water and contribute to further growth of algae. Thus, there will be a positive feedback. The higher the stock of phosphorous, the more the phosphorous released from the bottom. A better formulation of the dynamics is

$$\frac{dx}{dt} = a - bx + f(x),$$

where $f(x)$ is the feedback (Fig. 5).

It is quite clear that $f(x)$ is non-decreasing in x. Furthermore, when x increases, $f(x)$ will reach an upper bound because when all green plants in the bottom disappeared, increases in x will not release any more phosphorous from the bottom sediments. However, $f(x)$ has another most important feature. It is for small x convex and for large x concave. The reason for this is that when the stock of algae reaches a certain size, blue green algae or cyano-bacteria will take over and eventually dominate the stock of algae.[9]

The $f(x)$ function will therefore look as in the following figure:

The ecologists usually approximate $f(x)$ with the following sigmoid function:

$$f(x) = \frac{x^2}{1 + x^2}.$$

The dynamics of the eutrophication can then be written

$$\frac{dx}{dt} = a - bx + \frac{x^2}{1 + x^2}.$$

The remaining of this article will focus on the economic implications of this equation.

[9] For a detailed account of this, see Scheffer (1997).

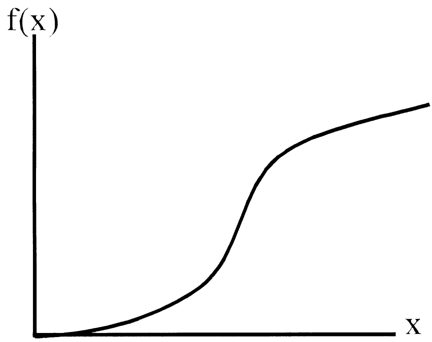

Fig. 5. The feedback function.

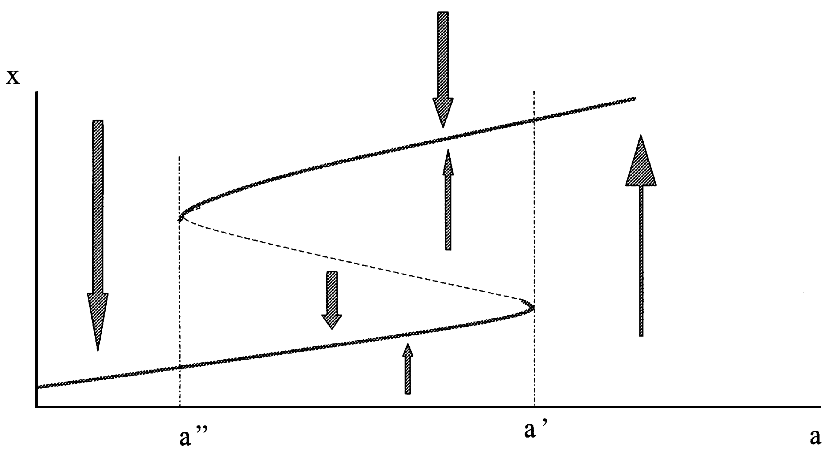

Fig. 6. Constant loading.

2.3. Steady states

We will in this section study the very special situation of constant phosphorous loading, that is the case when a can be regarded as constant. We will return to the dynamic adjustments to changes in a in the next section.

Let us begin by looking at the steady states, that is combinations of a and x, such that the stock of phosphorous in the lake remains constant. This will occur when $\mathrm{d}x/\mathrm{d}t = 0$, that is when

$$\frac{\mathrm{d}x}{\mathrm{d}t} = a - bx + \frac{x^2}{1 + x^2} = 0.$$

The locus of the implicitly defined relation between x and a is drawn in Fig. 6.

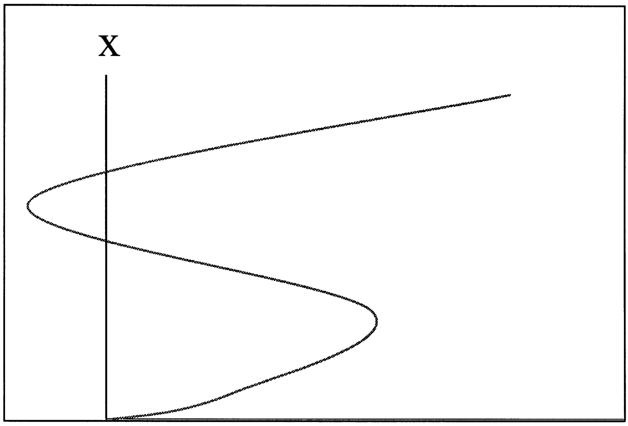

Fig. 7. Possible irreversibility.

It is clear that there are two bifurcation points in the system, a' and a'', and that the hatched line is unstable and will never be observed in nature. The two other parts of the curve are stable and there are therefore two different basins of stability of the system. If the constant loading exceeds a', the system will flip to the upper basin of stability, that is to a eutrophic state of the lake. In order to flip back to the original oligotrophic state, it is necessary to reduce the constant loading to a value lower than a''. Thus, the lake is also characterized by hysteria. It is not possible to return to the initial situation by just reversing the actions that in the first place changed the lake from the initial situation.

Assume that the lake is in an oligotrophic steady state, x'. How much can we perturb the runoff without reaching a bifurcation point? This amount is known as the resilience of the system and represent the buffer capacity of the system to exogenous shocks. If the resilience is exceeded, the lake will flip to a different basin of stability and with radically different quality characteristics.[10]

Depending on the parameters b and g, the diagram may look like Fig. 7. In this case, it is impossible to flip back to the oligotrophic state (because we cannot have negative loadings) and we have an irreversibility (if we cannot use any other techniques to reduce the stock of phosphorous).

Assume now that the community has to choose between different steady states. This is illustrated in Fig. 8.

Remember that a is good but x is bad, that is increased a means increased productivity in agriculture while increases in x means losses in amenities. Indifference curves will therefore have a positive slope. The optimum is with

[10] See Ludwig et al. (1997) for an extensive discussion of resilience.

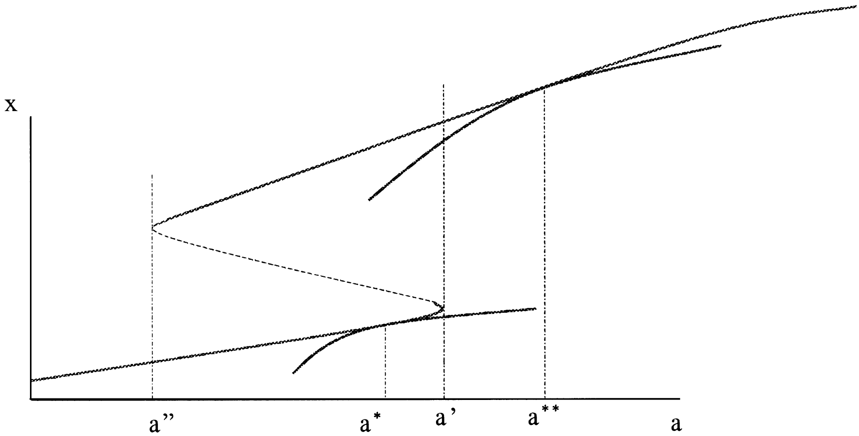

Fig. 8. Steady-state optima.

a loading equal to a^*, the indifference curve is tangent to the oligotrophic part of the curve . Assume now that a mistake is being made so that the loading exceeds a'. The eutrophic lake will then flip to the eutrophic state. If the cost of restoring the lake to the original state is too high, a^* will be the new optimum. It is the best situation given that the lake will permanently be in a eutrophic state. In this case, the mistake of a too high loading will create an economic irreversibility. The cost of undoing the mistake is too high.

2.4. Dynamic optimum

The flip from one basin of stability to another is not an instantaneous one but takes time (1–3 years) depending on the size of the lake. Thus, there are no discontinuities involved, but a rigorous analysis must take the adjustment towards equilibrium into account.

Let the instantaneous utility function be $u(x, a)$ and let the utility discount rate be δ. The social welfare function can then be written

$$W = \int_0^\infty e^{-\delta t} u(x, a)\, dt.$$

Optimum is defined as the path of phosphorous loading that will maximize W subject to the dynamics of the lake. This involves the application of Pontryagin's maximum principle. However, there will be in general different candidate equilibria to which the system may converge. This will create some technical problems. Brock and Starrett (1999) have characterized the optimal path completely and we will follow their analysis rather closely (although without all technical details).

Assume the utility function can be written

$$u = \ln a - cx^2.$$

Thus, the utility is separable in phosphorous loading and the loss in amenities from eutrophication.[11] The Hamiltonian can be written

$$H = \ln a - cx^2 + p\left(a - bx + \frac{x^2}{1 + x^2}\right),$$

where p is the co-state variable. The necessary condition for an optimum is that the partial of H with respect to a is zero:

$$\frac{\partial H}{\partial a} = \frac{1}{a} + p = 0$$

or

$$a = -\frac{1}{p}.$$

We also know that the co-state variable will satisfy the differential equation

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \left[\delta + b - \frac{2x}{(1 + x^2)^2}\right]p + 2cx.$$

From this, it follows that the loading of phosphorous must follow the differential equation

$$\frac{\mathrm{d}a}{\mathrm{d}t} = -\left[\delta + b - \frac{2x}{(1 + x^2)^2}\right]a + 2cxa^2.$$

We can now study the quality behaviour of the system in a phase diagram. It is convenient to interchange the axes so that from now on, the vertical axes will represent the loading a and the horizontal axes will represent the stock of phosphorous in the lake.

In Fig. 9, the two curves corresponding to stationary solutions to the two differential equations intersect only once. In this case it will always be optimal to take the lake back to an oligotrophic state, irrespective of where the original state is. The optimal trajectory is described by the hatched curve, and it converges to x^* irrespectively of the initial level of eutrophication. However, the curves can look different as is seen in Fig. 10.

Here there are three possible equilibria. However, it is easy to see that the middle equilibrium is unstable, but the two others are saddle points and potentially optimal steady states. The way of analysing problems with multiple

[11] Brock and Starrett discuss the general case.

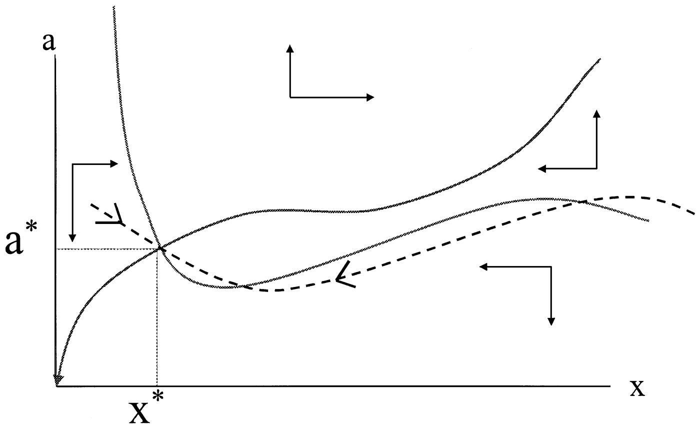

Fig. 9. Unique equilibrium.

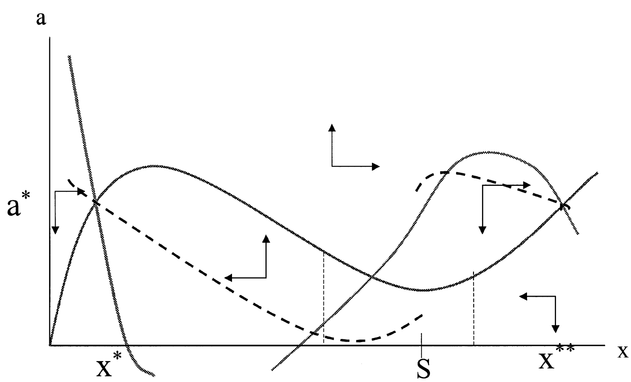

Fig. 10. Multiple equilibria.

equilibria resulting from concave–convex functions was introduced by Skiba (1978). He showed that there exists a level of initial x, here called S, such that if the initial stock is less than S, the optimal path will take the system to x^*, while if the initial stock is greater than S, the optimal path will take the lake to X^{**}. The possible optimal trajectories are shown by the hatched curves. If the initial stock happens to be S – the Skiba level – then the community will be indifferent whether approaching the oligotrophic equilibrium x^* or the eutrophic equilibrium x^{**}.

In this case, a mistake that makes the stock of phosphorous exceed the Skiba level should not lead to restoration of the lake! We have an economic irreversibility. Brock and Starrett have shown that it is possible for the two curves $\dot{x} = 0$

and $\dot{a} = 0$ can have a countable number of intersection, and is therefore quite possible that the optimal trajectory will be very complicated indeed.

2.5. Conflicts over the lake

There may be many obvious conflicts between different users over the lake. Obviously, farmers and recreationists will differ in their opinions on the optimal runoff of phosphorous to the lake. Another type of conflict will arise if there are many different communities or countries around the lake. This latter conflict is, of course, the same as the one that arises from a common property resource. As the dynamics of the lake will give some additional insights on common property resources, we will here explore this conflict. The first type of conflict will not be analysed, but a few comments will be offered later.

Thus, assume that there are no communities around the lake and that all communities have the same welfare function

$$W_t = \int_0^\infty \mathrm{e}^{-\delta t} u(x, a_i)\,\mathrm{d}t.$$

The dynamics of the stock of phosphorous in the lake will now be determined by the total amount of runoff of phosphorous, that is

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sum_t a_t - bx + \frac{x^2}{1+x^2},$$

where we sum runoff of phosphorous over all the communities. By symmetry, all a_i will be the same and equal to a. If there are n communities, then

$$\frac{\mathrm{d}x}{\mathrm{d}t} = na_t - bx + \frac{x^2}{1+x^2}.$$

Community i will seek to maximize its welfare W_i subject to this differential equation and its belief of what other communities will do. Here we will limit ourselves to the case of an open-loop equilibrium, that is we assume that communities will not receive any new information over time but they all will develop a plan for the whole future assuming that the other communities do the same. The equilibrium concept on this space of strategies is then the Nash equilibrium.[12]

The differential game can then be written as

$$\underset{\{a_t(t)\}}{\text{maximize}} \quad \int_0^\infty \mathrm{e}^{-\rho t}[\ln a_t(t) - cx(t)^2]\,\mathrm{d}t, \quad i = 1, 2, \ldots, n,$$

[12] This presentation will follow Mäler et al. (2000) closely. In their paper there is also an analysis of feedback equilibria.

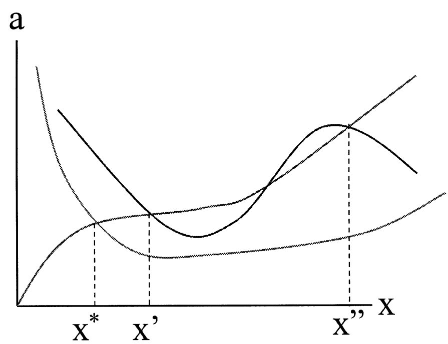

Fig. 11. Open-loop equilibrium with two communities.

subject to

$$\dot{x}(t) = \sum_{i=1}^{n} a_i(t) - bx(t) + \frac{x(t)^2}{x(t)^2 + 1}, \quad x(0) = x_0.$$

Applying the maximum principle to the differential game (6)–(7) yields the so-called open-loop Nash equilibrium (Basar and Olsder, 1982). The equilibrium conditions are (7) and

$$\frac{1}{a_i(t)} + p_i(t) = 0, \quad i = 1, 2, \dots, n,$$

$$\dot{p}_i(t) = \left[(b + \rho) - \frac{2x(t)}{(x^2(t) + 1)^2}\right] p_i(t) + 2cx(t), \quad i = 1, 2, \dots, n.$$

Substitution of (12) into (13), symmetry and multiplication by n yields

$$\dot{a}_{\mathrm{OL}}(t) = -\left[(b + \rho) - \frac{2x(t)}{(x^2(t) + 1)^2}\right] a_{\mathrm{OL}}(t) + 2\frac{1}{n}\, cx(t)\, a_{\mathrm{OL}}^2(t),$$

where a_{OL} again denotes the total loading level $\sum_i a_i$ at the open-loop Nash equilibrium e.

In order to analyse this system we will select numerical values for the parameters and simulate the system. Suppose that $b = 0.6$, $c = 1$, and $\delta = 0.03$. With these parameter values the optimal management will have only one steady state.[13]

The phase-diagram for the open-loop Nash equilibrium with the number of communities $n = 2$ is presented in Fig. 11. The $\dot{x} = 0$ curve and the $\dot{a}_{n=2} = 0$

[13] If we would have selected $\delta > 0.1$, there would have been multiple steady states.

curve now have three intersection points. (The curve $\dot{a} = 0$ is the corresponding curve for optimal management.) The left one and the right one are both saddle point stable and the situation resembles that of the analysis in previous section where also two Nash equilibria were found: one with an oligotrophic state of the lake and one with a eutrophic state of the lake.

The low phosphorus steady state x' (oligotrophic case) and the high phosphorus steady state x'' (eutrophic case) are saddle points, while the middle steady state will be unstable with complex eigenvalues. The instability of the middle steady state implies the existence of trajectories emanating from this steady state end converging either to the oligotrophic steady or to the eutrophic steady state.

Note that the difference between x^* and x' reflect the usual externality. As the two communities both are trying to be free riders, more of phosphorous will be added to the lake and as a result, the stock of algae will be higher in the open-loop equilibrium than in the optimal management situation. What is new here is the possibility that the lake will flip to a eutrophic state and end up at x''.

As in the optimal management analyses with three steady states, there will be a Skiba point S, so that if the initial stock of phosphorous is less than S, the open-loop strategies will take the lake to x' and if it exceeds S, the open-loop strategies will take the lake to x''. One way of interpreting this result is that if the initial stock is high enough, no community wants to take the cost of restoring the lake to the oligotrophic state, although it would benefit both to cooperate to do that. Instead, they will use x'' as a focal point and follow a strategy which will move the stock to x''.

Is it possible to introduce environmental policies to induce the communities to adopt strategies that will move the lake to x^*? Yes, one can design a tax on runoff of phosphorous such that the tax rate is a function of the stock of phosphorous in algae and such that the two communities together will move along the optimal trajectory. However, such a tax is extremely difficult to implement. Is there a simpler tax scheme? One possibility is to have a constant tax rate equal to the marginal damage from runoff in the optimal steady state. Such a tax will indeed induce the communities to steer the runoff in such a way that in the long run the lake will approach x^*. This tax scheme will, however, not induce the communities to follow the optimal trajectory and society will therefore experience probably unavoidable adjustment costs in restoring the lake to the optimal state. For further details on the constant tax rate see Mäler et al. (2000).

We have so far only considered free riding behaviour between different communities. A different conflict is between farmers and sportfishermen. Farmers would then be characterized by the utility function $\ln a$ and sportfishermen by the utility function $-cx^2$. Assuming that the farmers have the property rights, that is they are allowed to discharge any quantity of phosphorous into the lake, it follows that the sportfishermen's only possibility to improve their situation is to bribe the farmers to reduce the runoff. If we forget the free riding behaviour within the group of fishermen, the utility function of the group will be $-T(a) - cx^2$, where T is the bribe they have to pay the farmers in order reduce the runoff to a. The corresponding utility function for the farmers is $T(a) + \ln a$. This is a completely different situation from the one we have considered above. In particular, the bribe will in general change over time, and it may, therefore, be extremely difficult to implement due to the transaction costs. Therefore, the Coasean solution does not apply. Most probably, it will not even be possible to use a shortcut such as a bribe that will induce the farmers to maintain a constant runoff equal to the optimal runoff. If the lake is eutrophic, then such a bribe will not induce a flip of the lake to an oligotrophic state.

2.6. Water hyacinths

The shallow lake can of course be manipulated by policies that do not aim at the runoff. One possibility is to introduce pescevorous fishes. These will eat the planktovorous fishes and we will therefore experience a growth of zooplankton. However, plankton eat algae, and we may by that route reduce eutrophication of a lake. Thus, optimal management must incorporate both management of runoff of phosphorous and the biodiversity of the lake.

This same mechanisms apply to lakes infested by the water hyacinths. First of all, the carpet of hyacinths on the surface of the lake blocks out sunlight which eventually will kill the bottom flora. The result is that more nutrients will be available for the hyacinths. Indeed we have the same positive feedback as we studied in the shallow lake. Thus, effective control of the pest requires control of the nutrients. However, as already mentioned, it is possible to exterminate at least some of the hyacinths by introducing some alien species of insects. One can, of course, also remove the hyacints by using herbicides, although that may have substantial environmental costs.

Thus, the optimal management of lakes in southern and eastern Africa with regard to water hyacinths needs to focus both at nutrient control and the use of different species composition. The implementation of such management may be extremely difficult. In the case of lake Victoria, three different countries surround the lake, and none of the governments involved has control of the runoff of phosphorous. The runoff comes from quite many different sources – sewage, fertilizers, factories, decomposing organic matter (including dead hyacinths). Without a complete picture of the nutrient flows, the problem of hyacinths in that lake may never be solved.

What is needed (in view of the analysis of the shallow lake) are:

- Inventory of nutrient flows to the lake.
- Inventory of measures and associated costs of changing the nutrient flows.
- Inventory of measures and associated costs of directly removing the hyacinths.
- A good understanding of the feasibility of biological control of the hyacinths.

- A good understanding of the ecology, and in particular the dynamics, of the lake.
- Estimates of the damage costs from excessive growth of hyacinths.

Unless one takes such a system point of view, the hyacinth problem will never be solved.

3. Extensions

The analysis of non-linear dynamical ecosystem is rather new. The pioneer was C.S. Holling, who together with D.D. Jones and D. Ludwig (Ludwig et al., 1978) studied the interaction between the spruce budworm and forests in boreal forests in Canada. The dynamics was very similar the one presented in the previous section on the shallow lakes. In a later paper, Holling showed that a reduction in migratory bird populations could release an outbreak of budworms with potentially serious consequences for forest-based industries. The mechanism was as follows. A reduction in bird populations would reduce the natural control of budworms in the forests, and the population of budworms would increase until a bifurcation point had been reached. Then the whole system would flip into a state with much more budworms eating the trees. Eventually, the lack of food would reduce the budworm population but unless the reduction in biological control of the budworms could be compensated in a different way, the forest output would remain low.

J. Pastor of University of Minnesota has extended the analysis by studying the interactions between coniferous trees, deciduous trees, mooses, beavers, and budworms in an unmanaged and concluded that in the long run, the forest will turn into a chaotic state. Furthermore, such a state has certain advantages for the productivity of the forest. However, no one has analysed such a forest from an economic point of view as yet.

There are now evidence that some fisheries behave as they are in deterministic chaos and there are also some attempts to do economic analysis of such systems.[14]

For development economics, the work by Brian Walker and Charles Perrings is specially interesting. Walker has constructed models of the interactions between woody plants, grassy plants, grazing and browsing and forest fires. It turns out that the models are non-linear dynamic systems, although the non-linearities are quite different from those we have encountered in this article. Perrings has used Walker's models[15] for interesting economic analysis of management of rangelands.

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[14] See for example Clark (1995).

[15] See Perrings and Walker (1995, 1997).

4. Conclusions

The points that have been made in this article can be summarized in the following points:

- Ecosystems provide life supporting services that are essential for human well being but are rarely visible in economic terms as they usually do not have any well-defined property rights.
- In order to manage the ecosystems well, one needs to understand the basic dynamics of the systems.
- Ecosystem dynamics are often characterized by multiple equilibria and possible flips from one basin of stability to a another which in general imply hysteresis and in some cases irreversibilities.
- Optimal management will often, because of the complicated dynamics, be extremely difficult to implement and we need to know much more about simple rules of thumb for managing the systems.

References

Basar, T., Olsder, G.J., 1982. Dynamic Noncooperative Game Theory. Academic Press, New York.

Baskin, Y., 1997. The Work of Nature – How the Diversity of Life Sustains Us. Island Press, Washington, DC.

Brock, W.A., Starrett, D., 1999. Nonconvexities in ecological systems. Technical report. Beijer Institute, Stockholm.

Clark, C.W., 1995. Mathematical Bio-Economics: The Management of Renewable Resources.. Wiley, New York.

Daily, G.C. (Ed.), 1997. Nature's Services, Societal Dependence on Natural Ecosystems. Island Press, Washington, DC.

Daily, G., Ehrlich, P., 1995. Population extinction and the biodiversity crisis. In: Perrings, C., Mäler, K.-G., Folke, C., Holling, C., Jansson, B.-O. (Eds.), Biodiversity Conservation. Kluwer Academic Publishers, Dordrecht, pp. 45–56.

Folke, C., Kautsky, N., 1992. Aquaculture with its environment: Prospects for sustainability. Ocean and Coastal Management 17, 5–24.

Holling, C., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4, 1–23.

Holling, C., Schindler, D., Walker, B., Roughgarden, J., 1995. Biodiversity in the functioning of ecosystems: An ecological synthesis. In: Perrings, C., Mäler, K.-G., Folke, C., Holling, C., Jansson, B.-O. (Eds.), Biodiversity Loss: Economic and Ecological Issues. Cambridge University Press, Cambridge, pp 44–83.

Kay, J.J., 1991. A nonequilibrium thermodynamic framework for discussing ecosystem integrity, Environmental Management 15, 483–495.

Ludwig, D., Jones, D.D., Holling, C.S., 1978. Qualitative analysis of insect outbreak systems: The spruce budworm and forest. Journal of Animal Ecology 47, 315–332.

Ludwig, D., Walker, B.H., Holling, C.S., 1997. Sustainability, stability and resilience. Conservation Ecology 1, 7.

Mäler, K.-G., Xepapadeas, A., de Zeeuw, A., 2000. Lake model. Technical Report. Beijer Institute, Stockholm.

Perrings, C., Walker, B.H., 1995. Biodiversity loss and the economics of discontinous change in semi-arid rangelands. In: Perrings, C., Mäler, K.-G., Folke, C., Holling, C., Jansson, B.-O. (Eds.), Biological Diversity: Economic and Ecological Issues. Cambridge University Press, Cambridge.
Perrings, C., Walker, B.H., 1997. Biodiversity, resilience and the control of ecological systems: The case of fire driven rangelands. Ecological Economics 22 (1), 73–83.
Pimm, S., 1991. The Balance of Nature. University of Chicago Press, Chicago, IL.
Scheffer, M., 1997. Ecology of Shallow Lakes. Chapman & Hall, New York.
Skiba, A.K., 1978. Optimal growth with a convex–concave production function. Econometrica 46 (3), 527–539.