The Dynamic Response of Ecosystems to Human Use

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Abstract

Ecosystems are tremendously complex and quite unpredictable in their response to human activities. Irreversibility and hysteresis in the response of ecosystems are very important and can be treated in a rather generic way. The rule rather than the exception in a wide class of ecosystems is conceived in a multiplicity of stable states and the resulting nonlinearity of responses to change. For simplicity's sake, this response in hypothetical graphs can be represented with the ecosystem state as a function of the stress imposed by human use. The ecosystem may often come intact by increasing stress until it suddenly collapses when certain threshold values are exceeded. The main point illustrated in a very graphic approach for the behavior of systems between alternative stable states in shallow lake may capture a single dominant feedback mechanism for catastrophic response in a certain class of ecosystems. The basic properties of the catastrophic response in shallow lake are based on three assumptions: (a) turbidity augments with the nutrient level; (b) vegetation diminishes turbidity, and (c) vegetation vanishes as a critical turbidity is transcended. Various ecosystems tend to respond nonlinearly to stress increases resulting from human use. There are important implications for the interaction of ecosystems with economic systems. Our analysis suggests that the key ingredient is needed to give clear insight into ecosystem dynamic response to human use. A good ecosystem model discussed is essential to achieving sustainable use of ecosystems.

Keywords: Ecosystem; Shallow Lake; Critical Turbidity; Nutrient Loading.

INTRODUCTION

The earth is undergoing rapid environmental changes because of human actions. Based on emerging information about ecosystem services, humanity is entering the century of the environment. For human-modified ecosystems shaped by our activities and their side effect, ecosystems are immensely complex and completely unpredictable in their response to human use. A theoretical imperative for culture/ecosystem research in human ecodynamics (van der Leeuw, 2000) is the identification of historical processes contributes to modern environments. For humans dependent on the ecological systems of the planet, it is becoming increasingly obvious that numerous issues previously thought of as independent of the environment are intimately connected to it. Overall estimates of the human modification, management, or appropriation of nature range up to one-half of the terrestrial ecosystems (Vitousek et al., 1997) and one-quarter of the freshwater supply (Postel et al., 1996). Water stress is widespread in one-third of the world, where withdrawals exceed 20% of available supply (Commission of UN, 1997). Freshwater is one of the fundamental building blocks of life. Continued access to freshwater is required for drinking water, agricultural production, and industrial processes. Lakes represent cases of human influence on ecosystem function and provide unique opportunities for integrating humans into ecology (McDonnell et al., 1993; Collins et al., 2000; Kaiser, 2001).

It is very important for ecosystems in the case of lakes to different groups in human societies (“stakeholders”). For the shared use of ecosystems, stakeholders whose welfare or utility is associated with lake use. Human-modified lake ecosystems share a common set of traits such as : (1) recreational swimmers, boaters, fishermen, bird watchers, owners of homes bordering on the lake; (2) restaurants, hotels, campgrounds that serve recreational lake; (3) drinking water companies that use lake water as a source; (4) farmers who allow nutrients from fertilizers to pollute the water in the catchment area of the lake; (5) municipalities and industries that drain their waste water into the lake, and (6) users of the chain of rivers, lakes, and oceans that receive water from the outflow of the lake. For example, overfishing, dam building, irrigation, and urban, agricultural, and industrial contamination have turned great lakes into wasteland.

HUMAN IMPACT ON ECOSYSTEM

Human interaction with the physical environment has increasingly transformed ecosystem processes. Biodiversity plays a vital role for ecosystem functioning in a changing environment. Understanding the role of diversity for ecosystem functioning lies in quantifying interspecific tradeoffs that organisms face within the constraints of their environment. Environmental uncertainty refers to the cumulative effects of sequential impact events on human decision-making and adaptation. Lakes can be used by industries to get rid of waste water, but swimmers who want clean water can also process these polluted water. Fish require freshwater in their life cycle and habitat degradation adds further stress (Hinrichsen, 1997). Opportunities for restoring the health of fisheries include reducing pollution, adoption of lesser-impact fishing practices, and the protection/restoration of critical habitats. Before ending up in the ocean, the lake water passing through rivers and other lakes may affect many more distant stakeholders along the way. A conflict of interests often arises in the ways of using the ecosystem services by lowering the quality of the system for other users. Hence in and around shallow lakes, diversity may reflect social, economic, and cultural influences as well as those recognized by traditional ecological theory. The idiosyncrasy and complexity of ecosystem's response to human activities differ widely in terms of species composition, potential services to society, and threats to their resilience. Major ecosystem events can affect human activities in critical conjunctures that shape particular trajectories of social development. The potential response of ecosystem to human use can be treated in a rather generic way what called irreversibility and hysteresis. Conceptual developments have identified the need to quantify gradients of resource availability and disturbance that integrate lake use, legacy effects, and socioeconomic status, because these may mediate the human-environment interaction and influence resultant ecological conditions (Naveh, 2000). The rule rather than the exception in a wide class of ecosystems is conceived in a multiplicity of stable states and the resulting nonlinearity of response to change in conditions (Carpenter and Pace 1997; Tilman 1982). Catastrophic response in a certain class of ecosystems is usually due to single dominant feedback mechanism operating in lakes and often relatively easy to understand and predict. The range drawn from smooth to catastrophic response can be found in ecosystems. Possible responses of ecosystems to stress are imposed by human use. In view of the consequences for sustainable use, the case of shallow lake eutrophication focused on the catastrophic change as an example.

A MODEL FOR ECOSYSTEMS WITH ALTERNATIVE STABLE STATES

Factors that regulate phytoplankton dynamics in shallow, productive lakes are poorly understood. An assessment of the ecosystem consequences is complicated by the question of the best measure. Should structural characteristics such as overall diversity, species composition, size-frequency or trophic structure be used? Are ecological processes, whether resistance, resilience, perturbation, or some other measure more appropriate? Should ecological functions such as overall productivity, water and nutrient cycles, and reflectance be used?

The basic properties as lake of the catastrophic response of ecosystems in a simple mathematical model are captured to analyze how socioeconomic systems interact with ecosystem dynamics. For simplicity's sake, this response can be represented with the ecosystem state as a function of the stress imposed by human use (*x*). The very simple model capturing the catastrophic properties in a rather abstract way describes the change over tome of an unwanted ecosystem property *x*:

$$dx/dt = m - nx + lf(x),$$

where

m : stress imposed by human use promoting x;

n : the rate at which x decays in the system;

l : the rate at which *x* recovers again as a function.

The whole equation except a promoting *x* has been proposed to the internal dynamics. For lakes, *x* is considered as nutrients suspended in phytoplankton and causes turbidity. Therefore, the parameter *m* is represented as nutrient loading; *n* as nutrient removal rate; and *l* as internal nutrient recycling. This specific equation can only have multiple stable states if the maximum $\{lf'(x)\} > n$. For $l = 0$, the model has a single equilibrium at $x = m/n$. For $lf(x)$, this last term can cause the existence of alternative stable states. If $f(x)$ is a Hill function $f(x) = x^s / (x^s + g^s)$ that increases steeply at a threshold *(g)*, where the exponent *s* determines the steepness of the switch occurring around *g*.

IRREVERSIBILITIES AND HYSTERESIS IN ECOSYSTEMS

Human impact on ecosystems can be looked at the outcome of using such measures as changes in habitat, species composition, physical characteristic, and biogeochemical cycles. The response to increasing stress is frequently far from that impact will tend to increase more or less smoothly with intensity of use. Because of certain threshold values surpassed, the ecosystem may often appear to be untouched by increasing stress until it suddenly collapses. The ecological changes of ecosystem can be inferred with the reasons: (1) population cycle times and overall community turnover rates will shorten; (2) nutrient flow rates will increase; (3) resilience will increase but resistance will decrease, and (4) external agencies will increasingly govern community dynamics as the internal feedback linkages (Western, 2001). The response in simple graphs is represented to clarify differences in the way in which an ecosystem may response to changing conditions, and is also a rather minimal representation of the response of ecosystems to human impact. These hypothetical graphs that plot the ecosystem state as a function of the stress imposed by human use consider only one state variable and one stress factor for simplicity's sake.

The aspects of ecosystem state are of importance to human users. The consequences of human impact on such ecosystem properties as nutrient cycles and governing climate are harder to measure. For instance, turbidity of lake water, occurrence of toxic algae blooms, quality of the fish stock, and biodiversity in shallow lakes may be of interest to different groups of users. In addition, factors of species composition and zooplankton biomass are vital for the functioning of the ecosystem. Such as overloading the lake with phosphorus, this stress to the ecosystem will affect all of those characteristics and tend to follow the same coherent pattern in most lakes. Turbidity or phosphorus sequestered in algae is thought of one essential variable. The value of this kind variable may therefore be captured to roughly reflect the general state. Humans have greatly impacted the rates of supply of the major nutrients that constrain the productivity, composition, and diversity of terrestrial ecosystems.

By almost any measure, ecosystem properties are simplified such as diversity declining. The human use of nature can be through harvesting or destroying biomass such as fisheries and rainforest harvest. The effect of this human use is here described with stress, that is, the impact may be due to stressing the system by affecting its abiotic conditions of eutrophication, climate change and groundwater level reduction. The link between diversity and stability on the multitude of properties such as resistance, resilience, persistence, and variability leads us to ask too much of diversity, it is likely to miss the functional links between stress imposed by human use and ecological process (ecosystem). The horizontal axis of the figures may be considered as representing any of these stress factors.

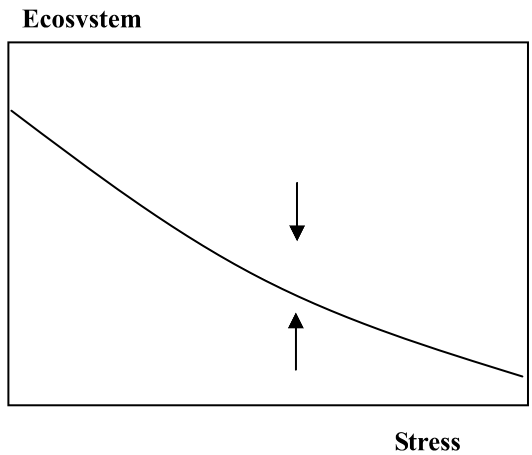

Figure 1 Ecosystem responding in a smooth, continuous way to increasing stress

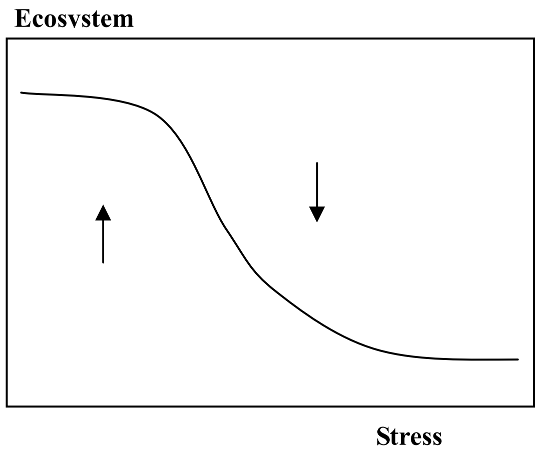

Figure 2 Stress approaching a critical level

Source: Scheffer, M., Brock, W. and F. Westley (2000) "Socioeconomic mechanisms preventing optimum use of ecosystem services: an interdisciplinary theoretical analysis", Ecosystems, 3, pp.451-471.

Figure 1 indicates that the state of some ecosystems may respond in a smooth, continuous way to increasing stress. There exists a negative relationship such that as stress increases, diversity of ecosystem decreases as along a curve that becomes less steep. Figure 2 indicates that the system relatively inert over certain ranges of conditions then responds more dramatically when that stress approaches a critical level.

Figure 3 and 4 both indicated that a significantly different situation arises when the response line is folded backward known as a "catastrophe fold". The ecosystem therefore with two alternative stable states over a range of environmental conditions implies, when the ecosystem is in a state on the upper branch of the sigmoid response curve, it will not pass to the lower branch smoothly.

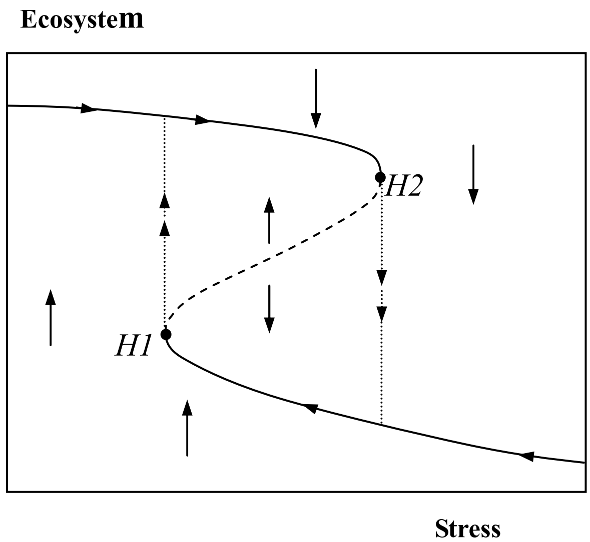

Figure 3 Ecosystem responding in a smooth, continuous way to increasing stress

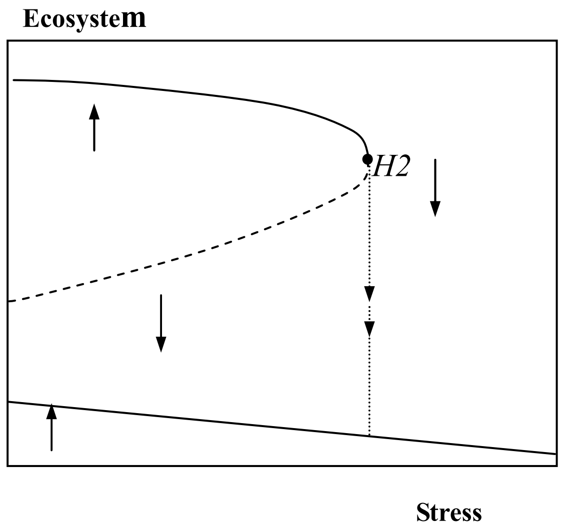

Figure 4 Stress approaching a critical level

Source: Scheffer, M., Brock, W. and F. Westley (2000) "Socioeconomic mechanisms preventing optimum use of ecosystem services: an interdisciplinary theoretical analysis", Ecosystems, 3, pp.451-471.

Instead, when increasing human use has altered the conditions sufficiently to pass the threshold (H2), what follows is a "catastrophic" transition showing vertical line with double arrow to the lower branch. Little change is observed in monitoring the system prior to this switch. It is difficult to obtain early warning signals of approaching catastrophic change due to the occurrence of such catastrophic shifts typically quite unannounced. On the other hand, in order to induce a switch back to the alternative state on the upper branch, restoring the stress level that occurred before the collapse (H2) is not sufficient and going back much further is instead beyond the other switch point (H1), where the system recovers by shifting back to the upper branch. Figure 4 indicates that the threshold level for a forward switch, but not for the backward switch, is within the range of conditions easily influenced by humans.

SHALLOW LAKE

Although there would be a continuum of responses, it is instructive to consider two ends of this spectrum: (1) the more immediate, or "ecological" responses; and (2) the more long-term, or "evolutionary" responses. Ecological responses would depend on the constraints and trade-offs that had structured a given community and on how these had changed. Many of the shallow lakes and ponds have become murky for their situation near populated areas. The use of fertilizer on the surrounding land and an increased inflow of waste water from human settlements and industries bring a consequence of eutrophication. Despite large investment in response to eutrophication control programs is made, many shallow lakes have shown little recovery. Actually even when the nutrient load is reduced to values well below those at which the collapse of the clear and vegetated state occurred, shallow lakes tend to remain in a highly turbid eutrophic state. A positive feedback in the development of submerged vegetation is probably the main explanation.

Let us consider a case of shallow lake in which water clarity is determined by competition for the composition and diversity of a plant community and light. Light is likely to be a primary factor in limiting the colonization by submerged plants (Skubinna et al., 1995). On the other hand, water clarity tends to increase in the presence of planets (Jeppesen et al. 1990). As a result there can be two alternative stable states. In a very turbid water, light conditions are insufficient for vegetation development; but once vegetation is present, the water clears up and the improved light conditions allow the persistence of a lush vegetation. This bi-stability has important implications for the possibilities of restoring eutrophied shallow lakes. Nutrient reduction alone may have little impact on water clarity, but an ecosystem disturbance like food web manipulation can bring the lake back to a stable clear state. Anthropogenic nutrient enrichment influences ecosystems worldwide by altering resource availability.

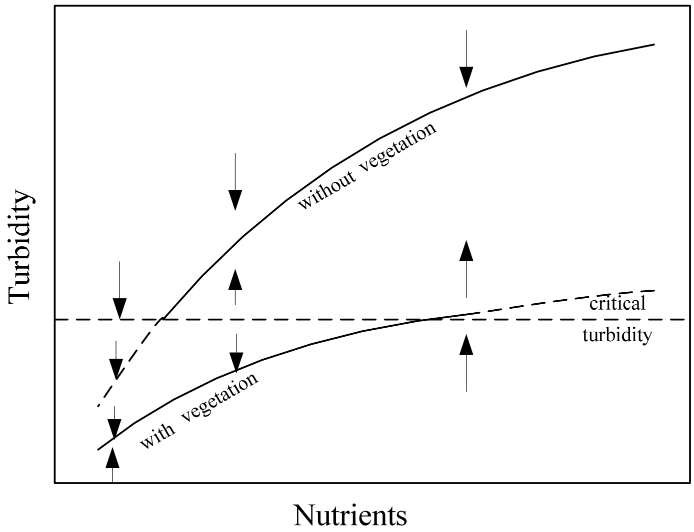

Figure 5: Graphic model for alternative stable states in shallow lakes.

Source: Scheffer, M., Brock, W. and F. Westley (2000) "Socioeconomic mechanisms preventing optimum use of ecosystem services: an interdisciplinary theoretical analysis", Ecosystems, 3, pp.451-471.

A theoretical framework for understanding the dynamics of shallow lake communities is from a combination of empirical studies, experimental work and model analysis. Although, as in most theoretical work, mathematical formulations play a role to capture the dominant mechanisms that are involved, the models that are used remain simple and most analyses are graphical rather than algebraic. A very simple graphic approach for the behavior of systems between alternative stable states seen in Figure 5 suffices to illustrate the main point in the shallow lake case. The ecosystem model could easily be integrated into a water quality model. Such models can help address question such as: (1) are there critical levels of diversity for a given ecological process? and (2) what critical thresholds exist for ecosystem properties in terms of species, processes, and area? The maintenance of diversity, process, and function in ecosystems will depend on the identification of these critical properties and thresholds. The graph is based on three assumptions: (1) turbidity increases as the nutrient level becoming high; (2) vegetation diminishes turbidity, and (3) vegetation vanishes as a critical turbidity is transcended.

Human domestication of ecosystems is greatly on high nutrient turnover. The turbidity of lakes is generally considered to be a smooth function of their nutrient status. Human activity will dominate biogeochemical cycles such as nutrients cycles across ecosystem boundaries. The first two assumptions indicate equilibrium turbidity drawn as two different functions of the nutrient level: one for a plant dominated situation, and one with a systematically higher turbidity for an unvegetated situation. The third assumption translates into a horizontal line representing the critical turbidity for vegetation survival. Above this line, vegetation will be absent, in which case the upper equilibrium line is the relevant one; below this turbidity, the lower equilibrium curve applies. The emerging picture shows that over a range of intermediate nutrient levels, shallow lakes can have two alternative equilibria: a clear state dominated by aquatic vegetation, and a turbid state characterized by high algal biomass. At lower nutrient levels, however, only the macrophyte-dominated equilibrium exists; whereas at the highest nutrient levels, there is only the turbid equilibrium without vegetation. If the lake is in a clear state (on the lower branch of the graph), an increase of the nutrient concentrations will lead to a gradual and moderate rise in turbidity until the critical turbidity for plant survival is reached (horizontal line). At this point, vegetation collapses and the lake “jumps” to the turbid upper branch. Reduction of nutrient s after this catastrophic transition does not result in a return of plants until the critical turbidity is reached again.

This backward switch, however, happens at a much lower nutrient level than the forward switch. Thus, reduction of the nutrient level to values at which the lake used to be clear and vegetated will not often lead to restoration of that state. This is indeed the experience of many lake managers. Compositional stability alone may be higher, but only because of the ever-higher costs in terms of nutrients. The absence of the clearing effect of vegetation explains that the water remains too turbid for vegetation to return.

This simple graphic model is analogous to the smooth sigmoidal catastrophe fold shown in Figure 3. The intuitively traceable lake example gives the way in which such catastrophic responses may arise. The graphic model is clearly a rather extreme simplification of the functioning of lake ecosystems.

CONCLUSIONS

Human-caused environmental changes are creating regional combinations of environmental conditions. The uncertainties over how human impact will affect large-scale ecosystem properties in turn clouds the evolutionary predictions. Ecological linkages are used to stress rather than a single measure. Ecology cannot yet tell us the full consequences of our activity, but it can at least map its dimensions and warn us to plausible threats. The challenge for ecology is to gauge the outcome of human action on ecosystem processes. If there is no link between biodiversity and human well-being, then the future may be grave for diversity but not necessarily for humanity. If that is the case, the fate of diversity will depend on human compassion and emotion rather than on human welfare. Ecological theory is essential in providing a robust, yet relatively simple explanation of ecosystems and their response to human activity. Community assembly rules and their relationship between ecosystem structure and process and how they vary biogeographically are basic to explaining overall diversity and ecosystem properties. More elaborate mathematical models and analysis of the behavior of many lakes confirm the main result: alternative equilibria are theoretically expected in shallow lakes. Larger numbers of species are probably needed to reduce temporal variability in ecosystem processes in changing environments. Identifying threshold levels of tolerance provides the guidelines on which sustainable development must be founded. A major future challenge is to determine how biodiversity dynamics, ecosystem processes, and abiotic factors interact. Ecosystem simplification is the ecological speciality of humanity and the reason for our evolutionary success.

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