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# On the scarcity value of ecosystem services

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**Abstract**

In this exploratory paper, we first make a case for considering the scarcity value of ecosystem services in the analyses of jointly determined ecological–economic systems. Next, we point out that insight into the scarcity value of an ecosystem service can be gained generally by examining the manner in which the state of an ecosystem responds to changes in environmental conditions. Following this, we specialize our discussion to the case of eutrophication in lakes. This leads us to pose and analyze a stochastic control problem of lake management in which ecological thresholds are salient. Finally, we show that this stochastic control theoretic framework can be used to obtain a numerical value that is closely related to the scarcity value of an ecosystem service provided by lakes.


*Keywords:* Ecosystem service; Ecosystem management; Lake; Scarcity value; Stochastic control

## 1. Introduction

More than three decades ago, in his classic paper "Conservation Reconsidered", Krutilla [42] argued for a refocused approach to environmental and natural resources. Rather than being concerned about the scarcity of exhaustible resources such as fossil fuels and minerals, he argued that we should focus on the preservation of unique natural environments. In a subsequent book, Krutilla and Fisher [43] focused on the preservation of selected wilderness areas, such as Hell's Canyon, the White Cloud Mountains, and Mineral King Valley.

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Thirty-five years later, during which time the world population has increased by 79% from 3.49 billion to 6.23 billion[1] and humans have transformed the biosphere in a significant manner,[2] it is time to refocus our perspective on conservation once again. In this paper, we contend that our focus today should not be on the conservation of pristine wilderness areas, per se, but on the conservation of ecosystem services and on their global distribution.[3] Ecosystem services are "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" [17, p. 3]. Examples of such services include the purification of air and water, the mitigation of floods and droughts, and the detoxification and the decomposition of wastes.[4] After making the case for the importance of the scarcity of ecosystem services, we discuss an approach to the measurement of its value, first in a general setting, and then in a specific example.[5] We also address the relevance of ecosystem services for the conduct of environmental policy.

A question that arises now pertains to the source of the scarcity.[6] In other words, are ecosystem *services* scarce or is it the *capacity* of an ecosystem to sustain the flow of a service that is scarce? To answer this question, consider the following two statements from prominent researchers in the area. Gretchen Daily [19, p. 372, emphasis added] tells us that the "pace of *ecosystem destruction*, and the typical irreversibility thereof on a time scale of interest to humanity, warrants substantial caution". Now, it is clear that the services under consideration in this paper are provided by ecosystems. Therefore, if the underlying ecosystem is destroyed, then it follows that the services provided by this ecosystem must either be nonexistent or, at the very least, scarce. Put differently, if one believes that the problem is primarily one of "ecosystem destruction", then it seems to us that we ought to be focusing on the scarcity of the services themselves.

Now consider the second statement. Recently, a team of ecologists and economists including Gretchen Daily, Paul Ehrlich, David Tilman, and Larry Goulder has said that "[e]cosystem services are being *impaired* and *destroyed* by a wide variety of human activities" (emphasis added).[7] According to this standpoint, both outcomes—impairment and destruction—are pertinent. The conclusion we draw from this second statement is that ecosystem *services* are scarce (because of the destruction aspect) *and* the *capacity* of an ecosystem to sustain the flow of certain services is also scarce (because of the impairment aspect). Because (i) both these statements support the position that it is the services themselves that are scarce and (ii) because the scarcity of these services is the more serious problem, in the rest of this paper, we shall focus on the scarcity of ecosystem services.

Although our focus in this paper is on incorporating ecosystem services into the economic paradigm, the perspective we take is interdisciplinary. The reader should note that traditional

[1] See http://www.census.gov/ipc/www/worldpop.html.

[2] For more on this point, see the individual chapters in [67].

[3] Additional support for this contention can be found in [21].

[4] An authoritative source on ecosystem services is Daily [18]. For related issues, see [20]. A prominent economist's perspective on the salience of ecosystem services is contained in [32].

[5] The reader should note that the scarcity value of an ecosystem service is not the same as its total value. As such, our approach in this paper is significantly different from the approach of Costanza et al. [14] who attempted to compute the total value of the world's ecosystem services.

[6] We thank an anonymous referee for raising this point.

[7] See http://esa.sdsc.edu/daily.htm.

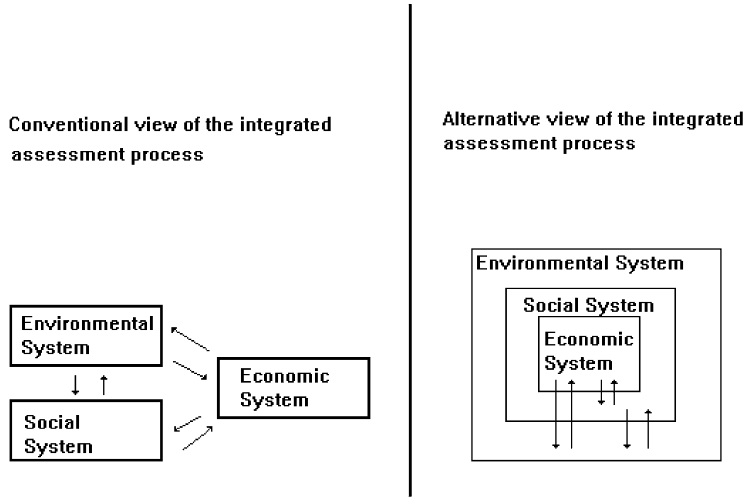


Fig. 1. Two views of the relationships among systems.

interdisciplinary research in the environmental sciences has concentrated on the development of linkages between social systems (such as the economy) and ecological systems. This is, in fact, the major emphasis of the new generation of integrated assessment models that link separate systems modules, which define the different processes of the various systems. While it may be convenient to characterize the different systems as inherently distinct, as Perrings [54], Levin et al. [46], and Batabyal [3] have noted, they are *not* separate systems. In fact, the social systems are embedded in the larger environmental system that governs the interaction of all ecological, social, and physical processes. This is illustrated in Fig. 1, where the left-hand side (LHS) of the diagram illustrates the conventional viewpoint, and the right-hand side (RHS) depicts a more comprehensive viewpoint, in which society is part of and embedded within a larger environmental system.

This conventional perspective of the inherent separateness of the two systems may be responsible for the widely varying policy prescriptions of environmental economists and ecologists. Economists argue that policy should be conducted by focusing on the most basic signals in the economic system, i.e., the prices. However, as Costanza and Folke [15] and Goulder and Kennedy [29] have pointed out, important ecological phenomena that affect the scarcity of ecosystem services are often *not* incorporated into prices. In contrast, although ecologists consider a wide variety of ecological phenomena, they rarely consider the behavioral forces which influence individual decision making. As such, they tend to focus on command and control policies. Having said this, it should be noted that ecologists are aware of the complex dynamics of the environmental system that are typically not analyzable by the calculus-based methods of economics involving marginal analysis. Moreover, they are also aware of the fact that the environmental system's *complex* dynamics substantially affect the states of the world in which the economic system operates.[8] We believe that by focusing on the scarcity associated with the

[8] For more on this, see [44,45].

provision of ecosystem services, both economists and ecologists will be able to find a common ground that can be the basis for meaningful future interdisciplinary research.[9]

Since the time of Ricardo and Malthus, economists have explicitly discussed the concept of scarcity. More recently, Hotelling [37] formalized the concept of scarcity and discussed the mechanism by which a market price serves as a signal of scarcity. Barnett and Morse [2] extended this work by demonstrating the way in which the increasing price associated with increased scarcity actually mitigates the scarcity problem. In all this prior work on scarcity, the focus has been on the scarcity of exhaustible resources, for which well-functioning markets generally exist. In recent times, concern has mounted about the scarcity of a second type of resource, namely, environmental resources that provide vital ecosystem services. Because no market exists for these environmental resources and hence for the associated ecosystem services, there is no readily available price (or nonprice) signal that can serve as an effective indicator of scarcity.

In this paper, we explore the importance of the scarcity of ecosystem services and suggest that by examining the manner in which the state of an ecosystem responds to changes in environmental conditions, we can come up with a numerical value of the scarcity value of an ecosystem service. Under some circumstances it may be possible to monetize this scarcity signal, but even when it is not possible to do this, an appropriate scarcity signal is better than no signal at all.

It is interesting to ask why we have not focused more carefully on the scarcity of ecosystem services. During the 1970s, Congress marked the citizenry's concern for the environment by passing the landmark Clean Air and Clean Water Acts (1972, 1977). In those days, we viewed environmental problems as local problems involving the use (or misuse) of local environmental resources. Although we recognized that unique environmental resources may have global value, we viewed the environment as a set of *independent* parts. As noted in [43], this view of the environment has been central in the subsequent development of techniques to value the environment.[10]

The approach of the discipline of environmental economics to valuing the services of preserved environmental resources—see [26,29]—has been to use revealed preference techniques such as the travel cost and hedonic pricing models or stated preference models such as contingent valuation or conjoint analysis to obtain a measure of the willingness to pay (WTP) for the relevant environmental resource. This WTP measure is supposed to be similar to the consumer surplus (CS) measure associated with market goods. If market goods are indeed sacrificed in order to implement environmental policy, then it makes sense to try to measure these values by means of a common metric.

However, before we become sanguine about the way in which we measure the value of environmental resources, let us ask ourselves a more basic question about the underlying values. Each year, thousands of ''Principles of Economics'' students are taught that economics is the study of the efficient allocation of scarce resources. Therefore, if we are to optimally allocate our environmental resources, we must understand the scarcity value of these environmental resources. As noted in Daily et al. [21], a critical aspect of this allocation process is to ensure the maintenance of vital ecosystem services. An examination of the scarcity value of ecosystem services is a salient

[9] For additional perspectives on the valuation of ecosystem services, see *Ecosystems* 3(1) 2000.

[10] For a more expanded discussion of this point, see *Ecosystems* 3(1) 2000.

problem because environmental resources and ecosystem services are essential for the maintenance and the productivity of the economic system. However, unlike exhaustible resources such as fossil fuels and minerals, ecosystem services are largely independent of the market system and hence their scarcity value is *not* incorporated into market prices.

The economic valuation techniques listed above can do an adequate job of measuring the scarcity of environmental resources with regard to the manner in which these resources contribute directly to the production of economic goods (such as the impact of air pollution on agricultural productivity, recreation, human health, and the general quality of life (altruistic values, bequest values, existence values, and so on)). If these were the only values associated with environmental resources then we could focus on further refining these revealed and stated preference techniques and use the knowledge generated by the implementation of these techniques to guide environmental policy for local and global environmental problems.

Even if the expressed WTP is a true measure of the current generation's willingness to trade-off ecosystem services for market goods, this WTP will *not* measure scarcity in a manner that is consistent with the way in which price measures the scarcity of a market natural resource such as a fossil fuel or a mineral. This is because the market price of an exhaustible resource will incorporate the future scarcity of this resource. Why? Because a supplier of the resource must be indifferent between selling the resource now and selling it in a future time period. If scarcity is increasing, then the seller will anticipate a higher future price and withhold the resource from today's market. This, of course, will increase today's price until the seller is indifferent between selling today and in the future. In other words, the opportunity cost of not having the resource available in future time periods is incorporated into today's price. *Neither* stated preference techniques such as contingent valuation *nor* revealed preference techniques such as hedonic pricing are capable of incorporating this opportunity cost into today's WTP.

In addition, if we look at the environment from a systems perspective,[11] then another important source of scarcity arises and revealed and stated preference techniques are ill-equipped to measure this scarcity value. If we accept the propositions that environmental quality contributes to the stability of ecosystems and that the stability of ecosystems in turn contributes to social welfare (because social systems are contained within and constrained by ecosystems), then, independent of the direct use of the environment, there must be a scarcity value associated with the degradation of environmental quality.

## 2. The importance of ecosystem services

Barnett and Morse [2] have argued that substitution is one of the major factors mitigating scarcity. As resources of a particular type become scarce, their prices rise and substitutes for these resources develop. Scarcity is mitigated by this substitution process, and it is often argued that this substitution process can even ensure sustainability in the sense of Brundtland [10]. For example, a clear suggestion emanating from the analysis in Hartwick [30] is that one can achieve sustainability as long as the scarcity rents accruing to exhaustible natural

[11] Recently, Simon Levin has suggested that we view ecosystems and the biosphere as complex adaptive systems. For more on this line of thinking, see [44,45].

resources[12] are reinvested in other forms of capital, such as human capital and human-made capital.

Despite the optimism associated with the literature on exhaustible resources, scarcity, and sustainability, there is no reason to believe that any of these scarcity reducing or sustainability generating phenomena are applicable to environmental resources. Increasing scarcity *cannot* trigger substitution away from ecosystem services because ecosystem services have no market price to trigger the scarcity signal. Moreover, one can argue that while human and human-made capital are effective substitutes for exhaustible natural resources, there is no reason to believe that human or human-made capital can be effective substitutes for either environmental resources in the production of ecosystem services, or for ecosystem services in their provision of system stability. Moreover, ecosystem ''services operate in intricate and little-explored ways that would be very difficult to substitute for using technology'' [19, p. 369].[13] Consequently, the most critical factor in sustainability is likely to be the maintenance of adequate stocks of environmental resources to ensure an adequate flow of ecosystem services. In sum, development paths that consume environmental resources intensively are likely to be unsustainable and development paths that conserve key environmental resources are likely to be sustainable.

It has rightly been said that ''natural ecosystems help to support society…'' [49, p. 11]. To this end, one can point to many real-world examples to make the case that ecosystem services are important for humans. For example, the annual floods of the Nile River replenish the productivity of the Nile flood plain soils and also provide the basis for an agricultural system that dates back several thousand years. The construction of the Aswan Dam has ended these annual floods and it has trapped the important sediments upstream of the dam, thereby impoverishing Egyptian agriculture and leading to massive migration into Cairo, with all the problems associated with urban poverty and unemployment. Consider a second example from the United States. Land-use decisions in the midwestern states have led to the loss of flood protection services provided by upstream wetlands. This loss has been considered to be a major factor in the recent intensive flooding of the Mississippi River and its tributaries. In particular, because the underlying systems involved are *complex* and *adaptive* [44,45], these problems may be more difficult than is commonly understood. Specifically, the problem of the loss of ecosystem services is likely to be complicated by phenomena for which small changes in economic activities—such as a small change in either the level of pollution or the pattern of land use—lead to large changes in the pertinent environmental systems.[14]

A good example of these nonmarginal responses can be found in the problem of greenhouse gas emissions. These emissions have been held responsible for causing (or at least intensifying) the cyclic *El Niño* and the *La Niña* climatic fluctuations that have profound implications for social welfare. In this example, marginal increases in carbon dioxide emissions lead to marginal increases in global temperature, but eventually a threshold is crossed and this leads directly to massive

[12] This paper distinguishes between two types of natural capital. The first type is the exhaustible resource such as a fossil fuel or a mineral resource. The second type of natural capital is the environmental resource, and this type includes ecosystem or physical systems such as forests and the ozone layer that provide essential services such as carbon sequestration, nutrient cycling, and protection from ultraviolet radiation.

[13] This point is also made in [31].

[14] For more on this, see [35,55,61].

warming in an area of the Pacific Ocean and to the destabilizing phenomena associated with *El Niño* and *La Niña*.[15]

An ideal treatment of the scarcity value of ecosystem services would develop a functional relationship between the level of ecosystem services and the value that these services provide. While this is the ultimate goal of our research, in this paper we attempt to develop some insight into the value of ecosystem services by measuring their scarcity value when critical ecological thresholds are crossed as a result of the continuance of economic activities.

## 3. Nonlinearity and the instability of ecological systems

Insight into the stability of ecosystems can be obtained by examining the nonlinear phenomena that govern the behavior of such systems. Changes in external conditions (climate change, loss of species diversity, etc.) lead to a gradual and, on occasion, even linear change in the state of some ecosystems. Other ecosystems may be relatively unresponsive to changes in external conditions, responding only when conditions approach or cross key thresholds. However, as Carpenter et al. [12] and Scheffer et al. [64] have pointed out, it is important to recognize that for certain environmental conditions, the response curve for many ecosystems is such that these systems have two alternate stable states demarcated by an unstable equilibrium that marks the boundary between the so-called "basins of attraction" of the two stable states. Examples of such stable states include oligotrophic and eutrophic states in lakes [11,48] and woody and grass dominated states in the case of rangelands [25,64]. This last (and important) class of ecosystems typically cannot move from one stable state to another smoothly. Instead, when external conditions change sufficiently so that a threshold is crossed, there is a "catastrophic" transition from one stable state to the other. This state of affairs tells us two things. First, "catastrophic shifts occur typically unannounced, and 'early-warning signals' of approaching catastrophic change are difficult to obtain" [64, p. 591]. Second, irreversible ecological thresholds can be crossed even when human actions result in small and gradual changes to the environment.

If there is only a single basin of attraction then an ecosystem will settle back into the same state after the occurrence of one or more stochastic events. However, consistent with the discussion in the previous paragraph, if there are alternate stable states, then the likelihood of a move from one state to another depends on the *size* of the basin of attraction associated with the first state. Specifically, if the size of the basin of attraction associated with this state is small, then even a minor perturbation can result in an ecosystem moving to a new equilibrium state. For example, competition by desert scrub may prevent the recovery of overgrazed arid rangelands. In this case, overgrazing permits the arid rangeland to be invaded by desert scrub and this invasion eventually results in the rangeland becoming a stable desert ecosystem.

Kahn and O'Neill [39] have used simple dynamic models and have demonstrated that ordinary types of ecological interactions (such as the interrelationships between competitors or those between predators and prey) can lead to nonlinearities that drastically affect the nature of an ecological equilibrium. If this is indeed the case, then nonlinearities in the ecological system will imply that nonlinearities in the economic system are much more likely to occur than most

[15] See [41] for an interesting related issue.

economists would ordinarily believe. Previous studies in environmental economics that have focused on nonlinearities [43] have associated them with large and discrete activities—such as damming a major river or massive mining projects in wilderness areas—that tend to be more isolated in nature.

Following the work of O'Neill et al. [52,53], and others, one can certainly provide powerful conceptual arguments that nonlinearities are likely to be important in the functioning of environmental systems. However, does the real-world evidence support the existence of such nonlinear dynamics in biological and environmental systems? The recent work of Scheffer et al. [64]—who provide helpful examples involving deserts, lakes, oceans, and rangelands—tells us that the answer to this question is an unambiguous yes. At the smallest scale, it is generally accepted that a type of nonlinear response causes periodic bursting in nerve cells [59] and rapid and transient behavior in microbial colonies [63,71]. At the ecosystem scale, Jones [38] argues that outbreaks of pests follow nonlinear dynamics. At the global scale, Crowley and North [16] demonstrate the existence of a fold catastrophe[16] in very simple models of ice cap dynamics and they argue that this accounts for rapid climatic changes in glacial–interglacial transitions.

The most conspicuous threshold at the landscape scale occurs at the ecotone. The ecotone is the tension zone where one vegetation type, for instance a grassland, changes suddenly into another such as a forest [24]. These sharp transitions have long attracted the attention of ecologists [51,60,62]. Changes occur as disturbances destroy the existing vegetation and open the opportunity for new vegetation to take over the site. With economic activities such as grazing, the probabilities shift slightly in favor of a new vegetation type.

As with other threshold phenomena, some ecotones are simply explained by sharp discontinuities in the abiotic environment. The simplest example of this is seen on mountains in the Northern Hemisphere, where the northern (colder) slope differs in vegetation from the adjacent southern (warmer) slope, yielding a sharp ecotone along the ridgeline. But as with other nonlinear threshold phenomena, some ecotones occur as sharp transitions even along gentle gradients in abiotic factors [33]. These ecotones are sharp because of competitive interactions within the system [22] and because a small change in the environment causes the system to move to a new stable state. As environmental changes occur over time, the ecotone responds by moving in space [9,23,65]. Pollen records indicate that past climate change has set off this kind of dynamics and caused a slow (5–200 km per century) migration of ecotones. The *Climate Change 2001* report [70] indicates that biomes may migrate 150–500 km north due to global warming.

The concern for nonlinear responses is also motivated by the broad spectrum of stresses being imposed on ecosystems by society [28]. Average temperature now is increasing faster than it has in the last 10,000 years [1]. The human economy uses 40% of net primary production [69]. Natural vegetation has been fragmented, making it more difficult to recover from natural disturbances [27]. The ozone shield has been damaged. Soil erosion is nearly universal, with soil loss rates significantly exceeding soil formation rates [57]. More than 50% of the world's tropical forests have been cut and the current rate of deforestation exceeds $168,000\ \mathrm{km}^2$ per year [28]. Some impacts, such as species loss, are irreversible [43] and technology is not available to repair large-scale damage [50].

[16] For more on fold catastrophes, see [38].

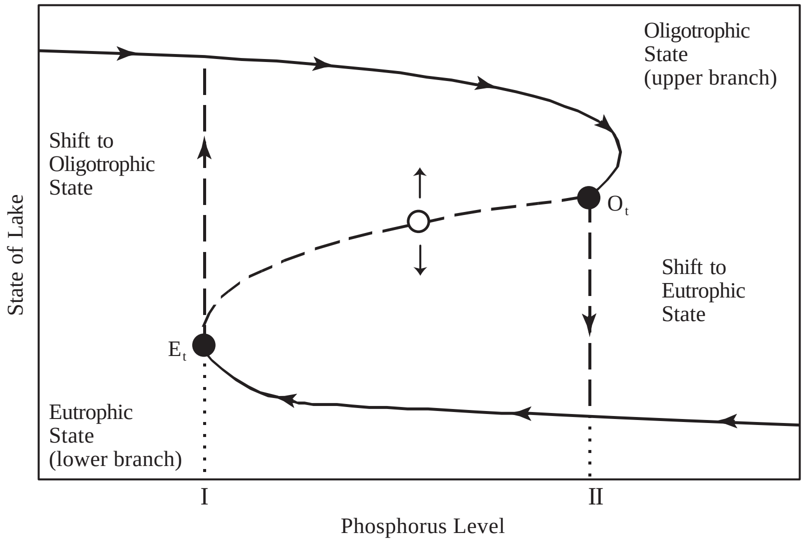


Fig. 2. Phosphorus deposition and alternate states of a lake. (Adapted from Fig. 2 in [11] and Fig. 2 in [64]).

Phillips [56] points out the importance of the ratio between the time required to recover from a disturbance and the time interval between successive disturbances. He suggests that a ratio of 1:10 is required for sustainability. The multiple stresses currently being imposed on the global system are both increasing the frequency and intensity of disturbances and decreasing the ability of ecosystems to recover. This twofold impact substantially increases the risk of threshold phenomena and of irreversibilities.

## 4. Measuring scarcity value

In this and the next section, we shall focus on lakes as our prototypical ecosystem. However, the reader should note that the ideas discussed here apply to many other ecosystems as well.[17] Fig. 2 shows the manner in which the equilibrium states of a lake ecosystem vary with changes in the amount of phosphorus in the lake. The horizontal axis denotes phosphorus in the lake and the vertical axis depicts the three possible states of the lake. As Maler [48] has noted, phosphorus occurs naturally in lakes. Even so, sewage, runoff from fertilizers—which contains phosphorus—used in agriculture, and other human actions often result in the deposition of significant additional amounts of phosphorus into lakes.

The pristine state of most lakes is one of clear water with significant amounts of submerged vegetation.[18] This clear water state is typically a stable state and a lake in such a state is said to be oligotrophic. In Fig. 2, this state is represented by the upper branch of the lake ecosystem

[17] Scheffer et al. [64] have shown that the ideas discussed here apply not only to lakes, but also to coral reefs, deserts, oceans, and woodlands.

[18] For more on this and related issues, see [11,64] and the many references cited in these two papers.

response curve. The submerged vegetation of an oligotrophic lake, and hence the oligotrophic lake itself, provide a number of valuable ecosystem services. Specifically, the submerged vegetation (i) reduces phosphorus in the water column, (ii) protects phytoplankton grazers such as the *Daphnia* and hence prevents the growth of phytoplanktons, and (iii) reduces sediment suspension in the water. As a result of the provision of these services, the lake stays clear and, from an anthropocentric perspective, this oligotrophic lake permits the conduct of activities such as fishing, recreation, and water sports.

When phosphorus is deposited into this lake, initially, green algae begin to grow. As more and more phosphorus is added, and this is shown in Fig. 2 by the arrowheads pointing in the rightward direction on the upper branch of the response curve, the water continues to be clear until a critical threshold is crossed. This threshold which marks the boundary of the oligotrophic state is denoted $O_t$ in Fig. 2. What is important to note here is that once this critical threshold is crossed, the water quality of the lake suddenly changes from clear to turbid. This turbid state is known as the eutrophic state and this state is shown in Fig. 2 by the lower branch of the lake ecosystem response curve. The dashed line between $O_t$ and $E_t$ denotes the third and unstable equilibrium. The state change from oligotrophic to eutrophic is denoted in Fig. 2 by the dashed arrow pointing in the downward direction from the threshold $O_t$. The reader should note that as the lake moves closer to $O_t$ along the upper branch of the response curve, the submerged vegetation in the lake gradually begins to die out and hence the services provided by this vegetation become increasingly scarce. In fact, beyond the threshold $O_t$, these services are either extremely scarce or altogether nonexistent.

What does this state of affairs mean for lake management? Clearly, given a choice between the more productive oligotrophic state and the less productive eutrophic state, a lake manager will prefer to keep a lake in the oligotrophic state. However, given that a lake is in the eutrophic state, this individual will want to take those actions that will move the lake under study to the oligotrophic state. In this context, it is relevant to note that a mere reduction of phosphorus concentrations is generally insufficient to restore the lake to the clear water state. Indeed, as Scheffer et al. [64, p. 592] have noted, "the restoration of clear water happens at substantially lower [phosphorus] levels than those at which the collapse of the vegetation occurred". So, if a lake manager attempts to move an eutrophic lake back to the oligotrophic state, then (s)he will generally have to contend with the fact that this lake demonstrates *hysteresis*.[19] In other words, the lake will revert back to the oligotrophic state if and only if phosphorus concentrations are altered to such an extent that the lake moves beyond the boundary of the eutrophic state. With regard to Fig. 2, this means that it will be necessary to take actions to move the lake leftward from the point marked II all the way past the boundary of the eutrophic state marked $E_t$. Only then will the lake shift back to the oligotrophic state and this is shown in Fig. 2 by the upward pointing dashed arrow from the threshold marked $E_t$.[20] Viewed in a different way, submerged vegetation

[19] As noted in [48, p. 655], hysteresis is the failure of a phenomenon to reverse itself when its underlying cause is reversed. The reader should note that the kinds of lakes that we are focusing on fall into the reversible or hysteretic category. It is generally not possible to reverse the process of eutrophication in irreversible lakes. For more on this, see [11].

[20] These thresholds are also known as attractors and as bifurcation points.

will gradually emerge in the lake and this will result, eventually, in the provision of the valuable ecosystem services mentioned earlier.

A concept that is now very important in discussions of the management of ecosystems is *resilience*. In this context, resilience refers to ‘‘the amount of disturbance that can be sustained [by an ecosystem] before a change in system control or structure occurs’’ [36, p. 50].[21] From the standpoint of lake management it is important to note that the productive oligotrophic and the unproductive eutrophic states can both be resilient. As such, it is important to comprehend what lake management means from a resilience perspective. The basic idea is stated succinctly by Carpenter et al. [12, p. 768]: ‘‘For a lake in the clear-water state, the challenge for managers is to increase or maintain the resilience of the clear-water state. For lakes in the turbid state, the challenge is to break down the resilience of the turbid state or shift the lake into the clear-water state’’.

In more technical parlance, we would say that the resilience of a state of the lake is the size of the stability domain associated with that state. Therefore, if the lake under study is in the oligotrophic state, then a manager ought to take those actions that ensure that the lake stays in the stability domain of this oligotrophic state and does not cross the threshold ($O_t$ in Fig. 2) and shift to the stability domain of the eutrophic state. Conversely, if the lake is in the eutrophic state, then actions ought to be taken so that the lake crosses the threshold ($E_t$ in Fig. 2) and moves out of the stability domain of this undesirable state into the stability domain of the desirable oligotrophic state.

A small literature in ecological economics [4,5,7] has documented the salience of thresholds in the behavior of dynamic and stochastic ecosystems. Despite this, to the best of our knowledge, there are very few formal models that explicitly analyze the connections between thresholds and ecosystem management. Consequently, we now adapt a model in Batabyal and Beladi [6] and present a preliminary analysis of optimal lake management in the presence of thresholds.

Before we proceed to the formal analysis, let us recall two points from our discussion thus far. First, ecosystem services provided by lakes are essential for the productivity of the economic system. For instance, in the Great Lakes region of the United States, the economic system includes productive farm lands and the associated agricultural activities on these lands. Second, because water clarity contributes to lake productivity and the productivity of lakes contributes to social welfare, one expects a scarcity value to be associated with a decline in lake water clarity. In the context of lakes, the pertinent ecosystem services include the many services provided by submerged vegetation, pollution dilution, recreation, and the productivity of lakes is, at least in part, a function of these ecosystem services.[22] Therefore, an increase in phosphorus deposition in the lake under study leads to a decrease in the provision of the above mentioned ecosystem services and this decrease leads to a decline in lake productivity.

[21] It is important to note that there are two meanings of resilience in the ecology literature. The sense in which we are using this term is due originally to Holling [34]. The other meaning of resilience is due to Pimm [58] and this interpretation focuses on stability near an equilibrium steady state, and resistance to disturbance and the speed of return to the equilibrium are used to measure this alternate notion of resilience. Recently, Holling [35] has referred to the Pimm [58] notion of resilience as ‘‘engineering resilience’’ and he has referred to his original (1973) notion of resilience as ‘‘ecological resilience’’. As indicated earlier, in this paper, the focus is on ecological and not on engineering resilience.

[22] For more on this see [12, p. 768].

With regard to Fig. 2, beyond the threshold $O_t$, our lake has changed its state and consequently its character is altered in a significant manner. In the resulting eutrophic state, the many ecosystem services such as pollution dilution are either not being provided at all or being provided at a very diminished level. Put differently, the capacity of the lake to, say, reduce phosphorus in the water column is minimal at the threshold $O_t$ and zero or close to zero on the lower branch of the ecosystem response curve. Consequently, on the lower branch of the ecosystem response curve, the phosphorus reducing service of the lake is truly scarce. Therefore, in our subsequent mathematical analysis we expect to identify a numerical value that is closely related to the scarcity value of this phosphorus reducing service as the level of phosphorus deposition in the lake rises, thereby moving the lake closer to the threshold $O_t$.

## 5. Optimal lake management, thresholds, and a scarcity value

### 5.1. Preliminaries

In the absence of regulation, sewage, and runoff from fertilizers used in agriculture results in ongoing phosphorus deposition in the lake under study.[23] This deposition of phosphorus over time eventually results in the steady-state level of the phosphorus reducing capacity of the submerged vegetation in the lake declining to zero. This unacceptably low level corresponds to some level of phosphorus deposition that effectively moves the lake beyond threshold $O_t$ and into the eutrophic state (lower branch in Fig. 2). Let us denote this low level by $L_R = 0$. With regard to Fig. 2, $L_R$ is somewhere to the right of the point marked II on the ecosystem response curve. As noted in [11,13], the lake manager would like to use a control variable $V$ (phosphorus deposition reduction, fish biomass reduction, sediment treatment, hypolimnetic oxygenation, biomanipulation, etc.) to raise the level of the submerged vegetation's capacity to reduce phosphorus in the water column from zero to $L_R + \gamma V$, where $\gamma > 0$ is a parameter. In terms of the two resilient states of the lake, our manager would like to use the control $V$ to move the lake from the eutrophic to the oligotrophic state.

Carpenter et al. [11], Lewandrowski et al. [47], and others have rightly pointed out that ecosystem management is a costly activity. Consistent with this viewpoint, we suppose that the use of the control variable $V$ for management purposes results in costs to society. We denote the cost of using the control $V$ by the differentiable cost function $c(V)$, and consistent with standard assumptions in economic theory (see [68, pp. 54–67]), we suppose that this cost function is increasing and convex. In symbols, this means that $c'(V) > 0$ and $c''(V) > 0$.

Let $X(t) = \{L(t) - L_R - \gamma V\}$ denote the deviation of the submerged vegetation's capacity to reduce phosphorus in the lake from the steady-state level $L_R = 0$, when the manager's control variable is $V$. To account for the stochastic nature of the submerged vegetation's phosphorus reducing capacity,[24] we model the evolution of the deviation $X(t)$ over time with a stochastic

[23] To keep the mathematics manageable, in the rest of this section, we shall focus on a single ecosystem service, namely, the phosphorus reducing service provided by the submerged vegetation in lakes. However, the reader should note that as we have pointed out at various points in the paper, lakes typically provide a multitude of ecosystem services to society.

[24] For more on the ways in which ecological uncertainty affects the ecosystem management problem, see [11].

differential equation.[25] Now, recall that the eutrophic state of a lake is a resilient state. Moreover, as discussed in Section 4, the lake in the eutrophic state also displays hysteresis. This tells us that the size of the stability domain associated with this eutrophic state is such that moderate attempts to move the lake to the oligotrophic state will only result in the lake flipping back into this unproductive state. Given this state of affairs, we expect the deviations $X(t)$ to exhibit a certain degree of mean reversion over time. Therefore, we suppose that the evolution of $X(t)$ can be described by the Ornstein–Uhlenbeck process.[26]. This means that $X(t)$ satisfies the linear stochastic differential equation

$$dX = -\eta X\,dt + \sigma\,dW, \tag{1}$$

where $\eta$ is the speed of reversion, $\sigma$ is the variance parameter, and $dW$ is the increment of a standard Brownian motion process. We wish to study the steady-state behavior of the deviation of the submerged vegetation's phosphorus reducing capacity from the steady-state level $L_R = 0$. From Proposition 5.1 in Karlin and Taylor [40, p. 219], it follows that the stationary probability distribution function of $X(\cdot)$ is

$$f_\infty(x) = \sqrt{\frac{\eta}{\pi\sigma^2}}\exp\left(-\frac{\eta x^2}{\sigma^2}\right). \tag{2}$$

Suppose that our lake manager has identified level I (this corresponds to threshold $E_t$ in Fig. 2) on the ecosystem response curve as the minimum acceptable level of the phosphorus reducing capacity of the submerged vegetation in the lake under study, given that this lake is *currently in the eutrophic state*. Viewed differently, this *minimum* acceptable level of the phosphorus reducing capacity is also the *maximum* acceptable level of phosphorus deposition in this lake, given that the lake is presently in the eutrophic state. The reader should note that it is necessary to move the lake from somewhere to the right of point II on the response curve to point I on this response curve (see Fig. 2) because the lake displays hysteresis. If the lake were reversible and not hysteretic, then to move the lake back to the oligotrophic state, the manager would not have to move the lake all the way to point I.[27] The manager's task now is to compute the probability that the phosphorus reducing capacity of this lake will actually stay above level I on the response curve when the control is $V$.

### 5.2. The optimization problem

To compute the above probability, let $f(l)\,dl = Prob\{stationary\ phosphorus\ reducing\ capacity\ \in (l, l+dl)\}$. This probability is the same as

$$Prob\{stationary\ value\ of\ deviation\ \in (l - L_R - \gamma V, l - L_R - \gamma V + dl\}. \tag{3}$$

Using Eq. (2), the probability in Eq. (3) can be simplified. This yields

$$f(l) = \sqrt{\frac{\eta}{\pi\sigma^2}}\exp\left\{\left(\frac{-\eta}{\sigma^2}\right)(l - L_R - \gamma V)^2\right\}. \tag{4}$$

[25] $X$ denotes the random variable and $x$ denotes a particular realization of $X$.
[26] For more on the Ornstein–Uhlenbeck process, see [40, pp. 170–173]; [66, pp. 524–534]
[27] See [11,64] for a more expanded discussion of these issues.

We can now state an objective for our manager. This manager chooses the control $V$, incurs cost $c(V)$, and maximizes the probability that the phosphorus reducing capacity of the lake is above level I, the minimum acceptable level. As indicated in Section 5.1, this means moving the lake in the leftward direction from somewhere to the right of point II on the response curve to the point marked I on this response curve (see Fig. 2). The reader will note that this is an ecological–economic objective. This is because the manager is choosing $V$ to maximize the likelihood that the phosphorus reducing capacity of the lake will be in the desirable range (an ecological criterion), at economic cost $c(V)$. Formally, our manager solves

$$\max_V \int_I^\infty \left[\sqrt{\frac{\eta}{\pi\sigma^2}}\exp\left\{\left(\frac{-\eta}{\sigma^2}\right)(l - L_R - \gamma V)^2\right\}\right] dl - c(V). \tag{5}$$

Now making the substitution $b = l - L_R - \gamma V$, our manager's optimization problem can be written as

$$\max_V \int_{I-L_R-\gamma V}^\infty \left[\sqrt{\frac{\eta}{\pi\sigma^2}}\exp\left\{\left(\frac{-\eta b^2}{\sigma^2}\right)\right\}\right] db - c(V). \tag{6}$$

The first-order necessary condition to this problem is

$$\gamma\left[\sqrt{\frac{\eta}{\pi\sigma^2}}\exp\left\{\left(\frac{-\eta}{\sigma^2}\right)(I - L_R - \gamma V)^2\right\}\right] = c'(V) \tag{7}$$

and the second-order sufficient condition is

$$\sqrt{\frac{\eta}{\pi\sigma^2}}\exp\left\{\left(\frac{-\eta}{\pi\sigma^2}\right)(I - L_R - \gamma V)^2\right\}\left\{\left(\frac{2\gamma^2\eta}{\sigma^2}\right)(I - L_R - \gamma V)\right\} - c''(V) \leqslant 0. \tag{8}$$

The first-order necessary condition (Eq. (7)) tells us that optimality requires the manager to choose the control $V$, so that the marginal economic cost to society of this control (the RHS of Eq. (7)) is equal to the marginal increase in the likelihood that the phosphorus reducing capacity of the lake will be above the minimum acceptable level I (the LHS of Eq. (7)). Let $V^*$ be the solution to Eq. (7). In order to shed light on the scarcity value of our lake's phosphorus reducing capacity, we now ask the following question: What is the steady-state probability that the phosphorus reducing capacity of the lake will be above the minimum acceptable level I? Put differently, what is the stationary probability that this lake's phosphorus reducing service will continue to be provided to society? If we know $\gamma, \eta, \sigma^2, L_R$, and the level I, then we can answer the above question by simply substituting $V^*$ into the first part of the maximand in Eq. (5). We will use this fact in the next section. For the time being, note that, in general, the nonlinear equation (7) cannot be solved explicitly for $V$. However, for some specifications of the cost function $c(V)$, this equation can be solved explicitly. Consequently, to illustrate our approach, we now discuss such a case.

### 5.3. An example

Suppose the cost function is exponential. That is, $c(V) = \exp(V)$. Now substituting $c'(V) = \exp(V)$ in Eq. (7) and then simplifying the resulting expression, we get

$$\gamma\sqrt{\frac{\eta}{\pi\sigma^2}}\exp\left\{\left(\frac{2\eta L_R I - \eta I^2 - \eta L_R^2}{\sigma^2}\right) + \left(\frac{2\gamma\eta I V - \gamma^2\eta V^2 - 2\gamma\eta L_R V}{\sigma^2}\right)\right\} = \exp(V). \tag{9}$$

Taking the natural logarithm of both sides of Eq. (9) and then rewriting the resulting expression yields a quadratic equation in $V$. That equation is

$$\left[\frac{\gamma^2\eta}{\sigma^2}\right]V^2 + \left[\frac{2\gamma\eta L_R + \sigma^2 - 2\gamma\eta I}{\sigma^2}\right]V + \left[\left\{\frac{\eta I^2 + \eta L_R^2 - 2\eta L_R I}{\sigma^2} - \log\left\{\gamma\sqrt{\frac{\eta}{\pi}}\right\}\right\}\right] = 0. \quad (10)$$

Denote the coefficient of $V^2$ by $\alpha$, the coefficient of $V$ by $\beta$, and the constant term by $\delta$. Then the solutions to Eq. (10) are

$$V_i^* = \frac{-\beta \pm \sqrt{\beta^2 - 4\alpha\delta}}{2\alpha}, \quad i = 1, 2, \quad (11)$$

with $\beta^2 \geqslant 4\alpha\delta$ for obvious reasons. Which of these two values of $V$ (only one value if $\beta^2 = 4\alpha\delta$) makes most sense for this maximization problem will depend on the parameters of the stochastic differential equation (Eq. (1)) describing the evolution of the deviations $X(t)$, and on the exogenously given phosphorus reducing capacity levels $L_R$ and $I$. For instance, it is tedious but straightforward to confirm that when $\gamma = 5,\ \eta = 1,\ \sigma^2 = 2,\ L_R = 0$, and $I = 1,\ \beta^2 > 4\alpha\delta$ holds. Therefore, Eq. (10) has two real roots $V_1^* = 0.4219$ and $V_2^* = -0.1019$. Substituting these values of $V_1^*$ and $V_2^*$ into Eq. (6) and then performing the necessary calculations[28] tells us that when $\gamma = 5,\ \eta = 1,\ \sigma^2 = 2,\ L_R = 0$, and $I = 1,\ V_1^* = 0.4219$ maximizes the manager's objective function.

We now come to the scarcity value of the ecosystem service under study, i.e., the phosphorus reducing capacity of our lake. As indicated previously, to get at this scarcity value, we first ask: What is the stationary probability that this ecosystem service will continue to be provided to society? This ecosystem service will continue to be provided to society as long as the phosphorus reducing capacity of our ecosystem is above level I. In this example, we know the (exogenously given) values of the parameters $\gamma, \eta, \sigma^2$, and the levels $L_R$ and $I$. Consequently, we can substitute these values and the optimal value of the control $V_1^* = 0.4219$ into the first part of the maximand in Eq. (5). After some algebra, we infer that the steady-state probability of the phosphorus reducing capacity being above level I is 0.8665.

Now, the stationary probability of not jeopardizing the provision of the ecosystem service in question is 0.8665. Therefore, the stationary probability of jeopardizing the provision of this ecosystem service is $1 - 0.8665 = 0.1335$. Note that this last probability corresponds to the situation in which the lake's phosphorus reducing capacity is virtually or actually zero and hence this ecosystem service is truly scarce. We can now proceed in one of two ways. Taking the simpler route, we can think of 0.1335 as the scarcity value of the phosphorus reducing service. Alternately, we can think of the scarcity value of the phosphorus reducing service as some function of the probability 0.1335. The simple route involves identifying the scarcity value of an ecosystem service as a probability. As such, this allows us to bound the scarcity value of an ecosystem service from above (the maximum is 1) and from below (the minimum is 0). In the alternate route, we think of the phosphorus reducing capacity's scarcity value as a function of the probability 0.1335. In subsequent research, we plan to analyze the properties of this function. For the moment, we note that this second route is more general and it includes the first route as a special case. This

[28] We used the tables in [8, pp. 494–503] to perform the required computations.

completes our preliminary analysis of optimal lake management in the presence of thresholds $O_t$ and $E_t$. We now conclude and provide a brief discussion of outstanding research questions in this area.

## 6. Conclusions

In this exploratory paper, we first made a case for seriously considering the scarcity value of ecosystem services in contemporary economics research. Next, we pointed out that insight into the scarcity value of an ecosystem service can be gained by analyzing the manner in which the state of an ecosystem responds to changes in environmental conditions. This led us to pose and analyze a stochastic control problem of lake management in which thresholds ($O_t$ and $E_t$ in Fig. 2) are salient. Finally, we used an example to show how this stochastic control theoretic framework can be used to obtain a numerical value that is closely related to the scarcity value of an ecosystem service.

Although this is a beginning, much additional research is needed before the approach of this paper is sufficiently developed to aid the environmental decision-making process. For instance, we used the stochastic differential equation for the Ornstein–Uhlenbeck process to model the deviation of our lake's phosphorus-reducing capacity from the steady-state level. Depending on the ecosystem under study, it may be necessary to adopt alternate modeling approaches. For instance, there is no a priori reason to expect the mathematical characterizations of a temperate estuary and a tropical forest to be identical. Even if general functional forms are similar, key parameters will typically be different.

The analysis contained in this paper can be extended in a number of directions. In what follows, we suggest three possible extensions of this paper's research. First, we analyzed the provision of a single ecosystem service, namely, the phosphorus reducing service provided by a lake. However, most ecosystems that humans use and rely on provide multiple ecosystem services. Consequently, it would be useful to generalize the analysis so that it is possible to analyze the simultaneous provision of multiple ecosystem services. Second, most economic analyses do not focus on the connections between external conditions, ecological thresholds, and the ecosystem response function. Therefore, it would be useful to further study the existence of these thresholds and their location along, say, the phosphorus deposition dimension. Finally, it would be useful to conduct research on the need for and the ways of monetizing the scarcity value of an ecosystem service. Studies of ecosystem management that incorporate these aspects of the problem into the analysis will provide additional insights into the nexuses between optimal ecosystem management and the scarcity value of ecosystem services.

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