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ABSTRACT

We now know that from a functional standpoint, jointly determined ecological-economic systems (ecosystems) cycle over time. However, because this recognition has been recent, the ecological economics literature contains very few formal studies of the management of cyclical ecosystems. Consequently, the objective of this paper is to use renewal theory to examine two ways of analyzing the optimal management of cyclical ecosystems.

JEL Classification: Q30, D80

Key words: Cyclical ecological-economic system, Optimal management, Renewal theory

ASPECTS OF THE OPTIMAL MANAGEMENT OF CYCLICAL ECOLOGICAL-ECONOMIC SYSTEMS[1]

1. Introduction

Recent research in ecology has led to major revisions in the theory of ecosystem[2] succession proposed by Clements (1916). The Clementsian view of succession envisaged an orderly process in which species assemblages progressively moved towards a climax. The assemblage and the characteristics of the climax species are determined by climate and soil conditions. In the Clementsian view of succession, the two primary ecosystem functions are *exploitation* and *conservation*. The exploitation function emphasizes the rapid colonization of recently disturbed areas, and the conservation function refers to the gradual accumulation of energy and materials.

However, as Holling (1986; 1995) and Holling et al. (1995) noted, recent research in ecology has stressed the need for two additional functions. One function is that of *creative destruction* or *release*. This concerns the release of accumulated biomass and nutrients by agents, such as forest fires, insect pests, and severe pulses of grazing. The other function is that of *reorganization* or *renewal*. This relates to the reorganization of nutrients so that these nutrients are available in the next phase of exploitation. As a result of the addition of these two functions, from a functional standpoint, the ecosystem succession picture can now be described by a four-box cycle (see Figure 1). It is important to note that during this cycle, biological time flows very unevenly. An

[2] In the rest of this paper, I shall use the terms "ecosystem" and "ecological-economic system" interchangeably.

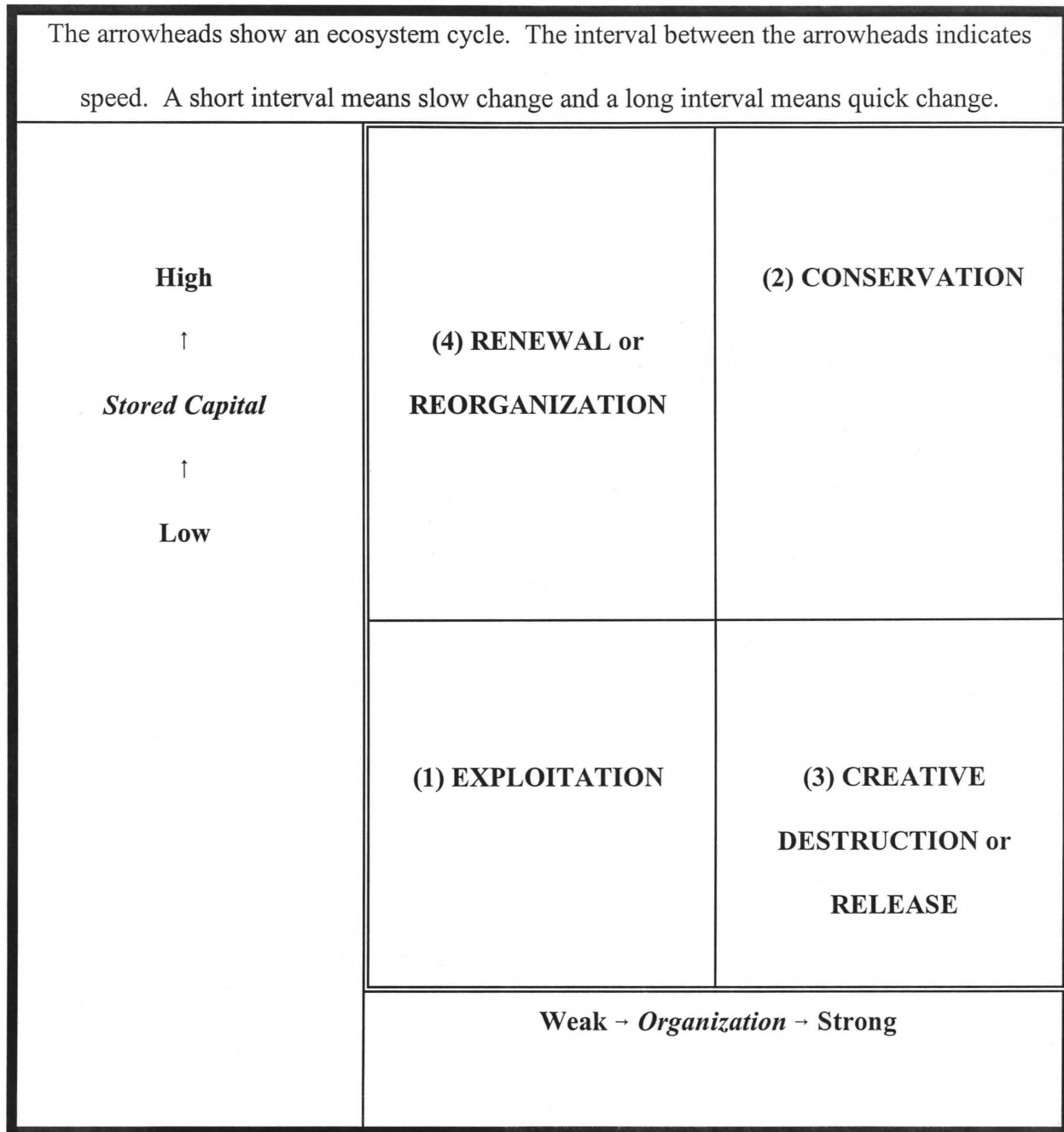| The arrowheads show an ecosystem cycle. The interval between the arrowheads indicates speed. A short interval means slow change and a long interval means quick change.		
High ↑ *Stored Capital* ↑ Low	**(4) RENEWAL or** **REORGANIZATION**	**(2) CONSERVATION**
	(1) EXPLOITATION	**(3) CREATIVE** **DESTRUCTION or** **RELEASE**
	Weak → *Organization* → Strong	

Figure 1. The ecosystem cycle

Source: Holling (1986, p. 307; and 1995, p. 22).

ecosystem moves slowly from exploitation (box 1) to conservation (box 2), then very quickly to release (box 3), once again quickly to renewal (box 4), and finally back to exploitation (box 1). In the process of moving from box 1 to box 2, the ecosystem becomes progressively more organized. Second, as the system moves from box 1 to box 4, the stored capital of biomass and nutrients in the ecosystem rises.

Given the existence of this cycle, if ecosystem management is to be effective, then it must incorporate this essential cyclicity in the design of management policies. In addition to this, there are two other features of ecosystems that managers need to account for in the design and the conduct of policies. The first feature is that ecological-economic systems are *jointly determined*. As Batabyal (1998) and Batabyal and Beladi (1998) noted, this means that the dynamics of the joint system reflect the nature of the connections between each of the two subsystems, i.e., the ecological and the economic subsystems. Consequently, shocks to the joint system generate a set of ecological and a set of economic effects, and these effects are interlinked. The extent to which these interlinked effects impact the stability of the joint system depends on the degree to which the two subsystems are connected. Perrings (1996) noted that highly connected ecosystems coevolve. Consequently, as compared to loosely connected ecosystems, the stability of highly connected ecosystems is more likely to be affected by ecological and/or economic shocks.

The second feature stems from the fact that our knowledge of the ecosystems that we seek to mange is incomplete. As such, *surprise* or unfulfilled expectations arising from the presence of uncertainty is inevitable.[3] The inevitability of surprise has important implications for ecosystem management. In particular, it tells us that management actions and policies need to be adaptable to

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[3]The term "surprise" is due to Holling (1986). For a more detailed account of surprise in the context of ecosystem management, the reader should consult Holling (1986; 1995).

changing circumstances. This need for adaptability is very important because as Holling (1995) noted, rigid management policies may be successful in the short run, but they inexorably lead to less resilient ecosystems and more dependent societies in the long run.

Despite the significance of managing jointly determined, cyclical ecosystems from an adaptive standpoint, there are very few formal studies of the management of such systems. In particular, there do not appear to be many studies that have analyzed the ways in which the management function is affected by the presence of uncertainty. For instance, consider the work of Dixon (1997) on watershed management, the work of Dixon and Lal (1997) on the management of coastal wetlands, and the work of Nelson (1997) on the management of drylands. While these papers are competent summaries of the empirical aspects of ecosystem management, they have very little to say about the formal aspects of the management of jointly determined, cyclical ecosystems.

Recently, Brown and Roughgarden (1995), Perrings and Walker (1995), and Batabyal (1998) have analyzed formal models of ecosystem management. While Brown and Roughgarden (1995) do provide an ecological-economic analysis of the problem of optimally harvesting a marine resource, their analysis is conducted in a deterministic setting. Consequently, this analysis is unable to address the issue of surprise or other stochastic aspects of the management problem. Perrings and Walker (1995) and Batabyal (1998) provided dynamic and stochastic analyses of the ecosystem management problem. Perrings and Walker (1995) considered the implications of discontinuous change in the mix of species in semiarid rangelands for the optimal management of livestock resources. Batabyal (1998) has used his stochastic characterization of resilience to show how an ecosystem manager can control the parameters of the management problem to optimally manage the flow of services provided by an ecosystem. These two papers do use an ecological-economic

approach to the management problem; moreover, both papers explicitly analyze the role of uncertainty in the ecosystem management problem. Nevertheless, neither paper analyzes the essential cyclicity of ecosystems.

Given this state of affairs, there is a clear need for studying the management of cyclical ecosystems. In this paper, I use renewal theory[4] to construct and analyze two models of the optimal management of cyclical ecosystems. Following Holling et al. (1995, p. 62), the first model's cycle may be interpreted as a renewal cycle.[5] In contrast to this, the second model analyzes a cycle of economic use.

2. The Optimal Management of Cyclical Ecosystems

2.1 The Ecosystem Cycle

Consider a stylized ecosystem which consists of a number of species. As discussed in section 1, this ecosystem cycles between the exploitation, conservation, renewal, and reorganization functions. As well, this ecosystem provides a flow of services to society over time. The economic utilization of these services results in shocks[6] to the ecosystem. I suppose that these shocks occur in accordance with a renewal process whose interarrival time is β. The economic utilization of the flow of ecosystem services results in benefits and costs to society. The social benefits include those that arise from activities such as boating, fishing, and grazing. The social costs arise from the fact that some of these shocks may result in surprises, and from the increased vulnerability of the

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[4]For more on renewal theory, see Wolff (1989, pp. 52-147) and, particularly, Ross (1996, pp. 98-162).

[5]Note that "renewal cycle" and "ecosystem cycle" are different names for the same phenomenon.

[6]Some of these shocks may result in surprises. In other words, these shocks may result in effects that are different from those that were expected by an ecosystem manager. For more on this, see Holling (1986).

ecosystem species to future shocks resulting from economic activities.[7] I suppose that whenever the number of shocks reaches *S*, the ecosystem cycle—shown in Figure 1—closes.[8] In other words, shocks can play the role of the creative destruction function in the ecosystem cycle. Further, I suppose that when our ecosystem has been subjected to *s* shocks, an ecosystem manager—or alternately, a benevolent social planner entrusted with the prudent use of the ecosystem—incurs variable costs[9] at the rate of $s\tilde{c}$ dollars per unit time. In addition to these variable costs, our manager incurs a fixed cost of *F* dollars when the cycle closes. The reader should think of *F* as the cost of renewal. Thus, from a management perspective, the social cost of economic activities is the sum of these fixed and variable costs. Our task now is to compute the long-run average social cost (hereafter *ASC*) of economic activities that are incurred by the ecosystem manager.

Recall that a cycle is completed whenever the number of shocks reaches *S*. As such, the description of events contained in the previous paragraph constitutes a renewal-reward process. The *ASC* can now be computed by applying the renewal-reward theorem to our problem.[10] The renewal-reward theorem tells us that the expected long run *ASC* is simply the expected cost incurred in a cycle divided by the expected time of that cycle. Put differently, we have

$$ASC = \frac{E[cycle\ cost]}{E[cycle\ length]}. \tag{1}$$

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[7] Put differently, the social costs arise from the potential reduction in the resilience of the ecosystem.

[8] One can also think of the closure of the cycle in terms of the strength of these shocks. In this way of looking at the problem, we would say that the cycle closes when the strength of the shocks reaches *S*.

[9] Here and elsewhere in the paper, costs refer to net costs, i.e., the difference between the gross social costs that economic activities impose on the ecosystem and the gross benefits that such activities bring to society.

[10] The renewal reward theorem is discussed in Ross (1996, pp. 132-140). For other applications of this theorem, see Batabyal and Yoo (1994; 1996).

Let X_s denote the time between the sth and the $(s+1)st$ shock in a cycle. Then the numerator on the right-hand side of equation (1) is given by

$$E[cycle\ cost] = F + E[1cX_1 + 2cX_2 + 3cX_3 + \ldots + (S-1)cX_{S-1}].\tag{2}$$

The right-hand side of equation (2) can be simplified to

$$E[cycle\ cost] = F + \frac{c\beta(S-1)S}{2}.\tag{3}$$

In order to compute the denominator on the right-hand side of equation (1), it suffices to note that the expected length of a cycle is simply the expected time it takes for S shocks to hit our ecosystem. Because the mean interarrival time for the shock renewal process is β, we get

$$E[cycle\ length] = \beta S.\tag{4}$$

Now combining our results from equations (3) and (4), we get an expression for the ASC. This expression is

$$ASC = \frac{F}{\beta S} + \frac{c(S-1)}{2}.\tag{5}$$

There are two things to note about equation (5). First, as we would expect, ASC equals the sum of the average fixed and the average variable social costs. Second, if the closure of the ecosystem cycle does not result in any fixed costs, then the mean interarrival time between shocks (β) has no effect on the ASC.

The ecosystem manager's goal is to put in place those controls that will, *inter alia*, improve the ability of the species in our ecosystem to withstand shocks from the pursuit of economic activities. Examples of such controls include the regulation of fishing equipment in a fishery and crop rotation in an agro-ecosystem.[11] By instituting such controls, our ecosystem manager is able

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[11]Other kinds of management controls will be discussed in section 2.2.

to affect S, the number of shocks until the closure of the ecosystem cycle. Formally, we have $S = S(\vec{U})$, where $\vec{U} = (u_1,...,u_n)$ is a vector of the n control variables.[12] The ecosystem manager's problem can now be stated. This manager solves

$$\min_{(u_1,...,u_n)} \frac{F}{\beta S(\vec{U})} + \frac{c\{S(\vec{U}) - 1\}}{2}. \tag{6}$$

Assuming that a regular minimum exists, the vector of optimal controls $(u_1^*,...,u_n^*)$ satisfies

$$S(u_1^*,...,u_n^*) = \sqrt{\frac{2F}{\beta c}}. \tag{7}$$

The second-order conditions to problem (6) are

$$\frac{2F}{\beta\{S(\cdot)\}^3} \frac{\partial S(\cdot)}{\partial u_i} > 0, \ i = 1,...,n. \tag{8}$$

The first-order necessary condition (equation (7)) tells us that the manager will choose the n controls so that the number of shocks required to close the ecosystem cycle equals the square root of twice the cost of renewal divided by the product of the mean interarrival time and the marginal cost of the shocks. Equation (7) also tells us that if the cost of renewal (F) increases, then the manager will choose the n controls so that the number of shocks required to close the ecosystem cycle is now higher than before. Finally, the first-order condition tells us that if either the mean interarrival time of the shocks (β) or the marginal cost of the shocks (c) increases, then the manager's optimal response will be to choose the n controls so that the number of shocks required to close the cycle decreases.

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[12]It is possible that the manager may incur certain costs in the process of managing the ecosystem. To keep the analytical framework tractable, I suppose that these costs can be subsumed in F.

I now model and analyze an economic use cycle. In this framework, the ecosystem manager uses policies to manage an ecosystem at specific points in time.

2.2 The Economic Use Cycle

Suppose that as in section 2.1, the economic utilization of the flow of ecosystem services results in costs and benefits to society. However, instead of attempting to influence the number of shocks that are required to close the ecosystem cycle, the manager now follows a different strategy. In particular, this manager attempts to determine the optimal length of the *cycle of use* that accompanies the pursuit of economic activities. Put differently, the manager uses time-based policies to minimize the *ASC* of economic activities. Examples of such policies include the regulation of fishing season length, moratoriums on grazing, the fallowing of agricultural land, and the temporal management of forest fires. Note that in contrast with the cycle of section 2.1, we are now analyzing an economic use cycle. Our task now is to compute the long run *ASC* that is incurred by the ecosystem manager when this manager's focus is on time rather than on shocks *per se*.

Once again, I appeal to the renewal-reward theorem. A use cycle is completed upon regulation, i.e., every T time periods. In order to compute $E[cycle\ cost]$, I first condition on $N(T)$, the total number of shocks that hit our ecosystem by time T. This yields

$$E[cycle\ cost/N(T)] = F + \frac{cTN(T)}{2},\tag{9}$$

and hence, the *ASC* is given by

$$ASC = \frac{F}{T} + \frac{cT}{2\beta}.\tag{10}$$

Equation (10) tells us that when the object of study is an economic use cycle, the mean interarrival time (β) affects the *ASC*, irrespective of whether society does or does not incur fixed costs from the closure of the use cycle.

To determine the optimal length of a use cycle, for example, the optimal length of a fishing season, the ecosystem manager will choose *T* to minimize the *ASC* in equation (10). In other words, this manager solves

$$\min_T \frac{F}{T} + \frac{cT}{2\beta}. \tag{11}$$

Once again, assuming a regular minimum, the first-order necessary condition to problem (10) is

$$T^* = \sqrt{\frac{2\beta F}{c}}, \tag{12}$$

and the second-order condition is

$$\frac{2F}{T^3} > 0. \tag{13}$$

Equation (12) tells us that the optimal length of an economic use cycle equals the square root of twice the product of the mean interarrival time and the fixed cost of closing the cycle divided by the marginal cost of the shocks. This equation also reveals the opposite effect that the marginal cost of shocks (*c*), and the fixed cost of closing the use cycle (*F*) have on this optimal cycle length. As the marginal cost of shocks rises, *T** falls. To interpret this result, consider the case of a fishery. The result says that as fishing becomes more costly to society—possibly because the intensity with which it is being pursued rises—a fishery manager responds optimally by reducing the length of the fishing season. In contrast, a rise in the fixed cost of closing the use cycle has the effect of increasing the length of the use cycle. One kind of fixed cost that is associated with the closure of a use cycle is the cost of enforcement. In a fishery this might be the cost borne by a manager to

ensure that no boats are fishing after the expiry of the fishing season. The above result says that if this cost rises, then *ceteris paribus*, the manager will increase the length of the use cycle. Finally, an increase in the mean interarrival time of shocks, (β), lengthens the use cycle.

2.3 Discussion

In this paper, I considered two ways of analyzing the management of cyclical ecological-economic systems. The model of section 2.1 examined the management function in the context of Holling's (1986; 1995) four box ecosystem cycle. The model of section 2.2 looked at management in the context of an economic use cycle. These models are abstractions; consequently, they do not tell us everything about the complex world of ecosystem management. The study of ecosystem management is complicated by a number of factors, and it is not possible to analyze all these factors in one or two models. As such, I now briefly discuss four factors that are relevant to the study of ecosystem management.

First, it is important to note that even when a researcher thinks that he or she has identified and specified a management problem correctly, this may not be the case. Second, all theoretical inquiries necessarily have practical boundaries, and this fact ought to be recognized. For instance, the optimal cycle length that is identified in equation (12) may not in fact be optimal because the model does not account for shortsightedness and human greed in the context of ecosystem management.[13]

Third, as indicated earlier, Holling (1986) observed that surprise is an essential aspect of ecosystems. Fourth, Holling (1995) also observed that the short-run success in managing an

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[13]For more on this, see Ludwig et al. (1993).

ecosystem can lead to the long-run collapse of the same ecosystem. These two observations should alert us to the fact that the efficacy of managerial actions is circumscribed by our limited ability to predict the future behavior of ecosystems and our inadequate understanding of the functioning of ecosystems. As Ludwig et al. (1993), Holling (1995), and others noted, this means that we should be cautious in our approach to ecosystem management, and we should implement management policies that are adaptable.

3. Conclusions

This paper addressed some aspects of the optimal management of cyclical ecosystems from a—hitherto unstudied—renewal theoretic perspective. In particular, the renewal-reward theorem was used to analyze the management function in the context of an ecosystem cycle and an economic use cycle. In a recent paper, Dasgupta (1996, p. 392) lamented "the neglect of ecological matters in economic modelling." It is hoped that the analysis contained in this paper will go some distance in filling this lacuna.

The analysis of this paper can be extended in a number of different directions. In what follows, I suggest two possible extensions. The model of section 2.1 looked at managerial policies that might be called "shock based." In section 2.2, the focus was on "time-based" policies. The economics literature on domestic environmental regulation in the presence of uncertainty has demonstrated the superiority of *mixed* control instruments in some situations. This means that a control that is part-price and part-quantity is sometimes superior to a pure price or a pure quantity control.[14] Is this insight relevant in the context of ecosystem management? This is a question on

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[14]A tax is an example of a price control and a quota is an example of a quantity control. For more on price versus quantity controls, and the efficacy of mixed controls, see Batabyal (1995).

which additional research is needed. This research will shed light on the desirability of adopting policies that are, for instance, "shock based" and "time based."

Interconnected ecosystems are poorly understood by practicing ecosystem managers. *Inter alia*, this is because ecosystem managers have to guess the values of the parameters of theoretical models. I have not discussed the problem of estimating the parameters of this paper's models so that the resulting models are useful in terms of their predictive power. Clark (1990, p. 340) noted the importance of this "identification" problem in the context of fisheries. However, this identification problem is more general and it applies to all ecosystems. Consequently, coordinated interdisciplinary research by ecologists and economists is needed to make theoretical models more useful from a practical standpoint.

Studies of ecosystem management that incorporate these aspects of the problem into the analysis will permit richer analyses of the management of cyclical ecosystems. In turn, such studies will enable a researcher to provide more concrete guidance about the desirability of alternate ways of managing ecosystems.

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