ECONOMICS OF RENEWABLE NATURAL RESOURCES

Jon D. Erickson, *Department of Economics, Rensselaer Polytechnic Institute, Troy, NY, USA*

Keywords
Renewable resources, dynamic optimization, resilience, fisheries, forests, eutrophication, adaptive management, open access, option value, irreversibility.

Contents

Glossary

Adaptive cycle: A characterization of renewable system behavior where patterns of growth and exploitation are captured by increasing connectedness among their components, eventually leading to release and reorganization of resources.
Discount rate: A measurement of human preference for near term over longer term benefits or reduced costs.
Dynamic optimization: A method of economic analysis used to determine the most efficient allocation of resources over time.
Economic profit: A measure of revenues over costs that takes into account both explicit and implicit costs and benefits.
Faustmann rotation: The optimal solution to the infinite-horizon timber harvest, where the marginal benefits of waiting are equated to the marginal opportunity costs of delaying both the current stand and all future stands.
Marginal value: The net benefit of an incremental change in the level of a resource stock or harvest.
Natural capital: Resources not produced by humans available to support economic activity (e.g. land, water, air, minerals, climate, solar energy).
Option value: The economic value of delaying an investment decision.
Renewable natural resource: A resource from nature useful to human economies that exhibit growth, maintenance, and recovery from exploitation over an economic planning horizon
Resilience: The ability to maintain a given state when subject to disturbance.

Summary

Renewable natural resources include those resources useful to human economies that exhibit growth, maintenance, and recovery from exploitation over an economic planning horizon. The economics of such resources has traditionally considered stocks of fish, forests, or freshwater, much like a banker would tally interest on cash deposits. From an economic point of view, the management of biomass, soil fertility or aquifer depth has been forced into a framework of discounted, marginal, zero profit valuation. Economic value has been discounted to account for a positive time preference. Only marginal value (that of the next unit) is considered relevant to market-based decisions. And all economic profits (including a normal return to factor inputs) should be driven to zero to maximize the sum of consumer and producer surplus at a social optimum.

This framework can aptly be described as dynamic optimization and expanded to include risk and uncertainty, a social (vs. private) rate of time preference, non-market values, and systems without bias toward equilibrium. However, the type of management recommendations stemming from this conception of renewable resource systems have tended to include policy instruments that seek to influence decisions at the margin, often ignoring the more complex, non-linear, unpredictable relationships between economy, society, and the environment, to the detriment of long-term sustainability goals. An alternative view of natural resource economics has emerged from a systems view. An interdisciplinary understanding of feedback loops, discontinuities, and episodic change results in contrasting management recommendations focused on managing system parameters for resilience, rather than squeezing out the last ton, board-foot, or cubic meter of a natural resource.

1. Introduction

The principal economic question in the management of renewable natural resources has been: How much of a resource should be harvested during the present vs. future time periods? Time is typically considered over the horizon of a single representative manager or economic operation. For instance, in ocean fisheries the economic question has been how much to harvest this season and how much to leave in the sea as a source of future growth next season. For a commercial forest operation, the economic question has concerned the length of time between harvests that maximizes a forest owner's profits. Similar examples comparing discounted income flows could be considered for renewable water, soil, or animal resources.

The question of when and how much to harvest has been posed as a balancing act between current and future benefits and costs. To strike this balance, economists have used methods of dynamic optimization (i.e. the best allocation over time). A renewable resource problem is typically framed as a maximization of some single measure of net economic value over some future time horizon, subject to the natural dynamics of the harvested resource, an initial stock size, a target for the end of the planning horizon (or a limit in the case of an infinite-time horizon), a measure of time preference, and other relevant market, price, and technology constraints. Advances in the treatment of risk and uncertainty, measurement of social versus private time preference, capture of non-market amenities, and analysis of non-equilibrium behavior have further extended this paradigm of efficient allocation.

The goal of economic efficiency – where the marginal benefits of a particular time path equate to the marginal costs – has been nearly singular in most economic models of renewable resources. These traditional economic concepts for the management of manufactured capital have been applied to natural capital, creating a concern for only the flows from natural capital (i.e. materials and energy) rather than the maintenance of capital stocks (i.e. life-support systems, regenerative capacity). However this focus on flows has been criticized as shortsighted and akin to living off capital rather than income. In contrast, a more complex view of renewable resources has emerged from a natural science perspective with an expanded focus on the scale of impact and resilience of ecosystem services. Recognition of complex interdependence on natural capital instead focuses on the resilience of non-substitutable capital stocks necessary for long-term economic activity. This adaptive systems perspective argues for renewable resource management regimes designed around the control of system parameters within domains of stability rather than targets for marginal extraction. Admittedly, a parametric management approach can forgo un-recovered economic profits, whereas marginal management by definition will push a competitive resource industry to a zero economic profit condition. However, if market efficiency is not the only goal of a management plan, then the adaptive systems perspective can aid in avoiding collapse of complex natural systems.

This article will first outline the essential elements of the dynamic optimization tradition of renewable resource economics. A summary of the fundamental equation of renewable resources highlights the essence of an efficient, market-based approach to management. Examples from fisheries and forest management are included to demonstrate the type of decision rules reached in this framework. Next, the treatment of stochastic change in renewable resource systems is briefly summarized in an optimal control framework. Finally, the adaptive systems management perspective is outlined, with an example of lake management highlighted in contrast to the optimal control perspective. Concluding remarks are offered in reference to the current status of renewable natural resources around the world.

2. Dynamic Optimization

Let a renewable resource X at time period t be described by the following discrete-time, first order difference equation:

$$X_{t+1} - X_t = F(X_t) - Y_t \quad (1)$$

where $F(X_t)$ represents a net growth function (i.e. birth less mortality), and Y_t is the period t harvest. Each period's addition to the current stock is estimated as the difference between growth and harvest. If harvest consistently exceeds growth, then the renewable resource must be in decline. Similarly, if growth consistently exceeds harvest, then the renewable resource is expanding. The existence and stability of steady-states, where harvest exactly equals growth in each time period (Y=F(X) for all t), can also be found in this framework and is often the focus of analysis.

For many renewable resources, the growth function is typically specified as dependent on an intrinsic growth rate (r), a carrying capacity (K), and periods of increasing and decreasing marginal additions to stock. In resources such as forests, a period of negative growth can also be specified to account for the effects of aging and decay. A popular growth curve of analysts is the logistic form:

$$F(X_t) = rX_t(1 - X_t/K) \quad (2)$$

and is represented in Figure 1, with the parameters normalized at r = 1 and K = 1.

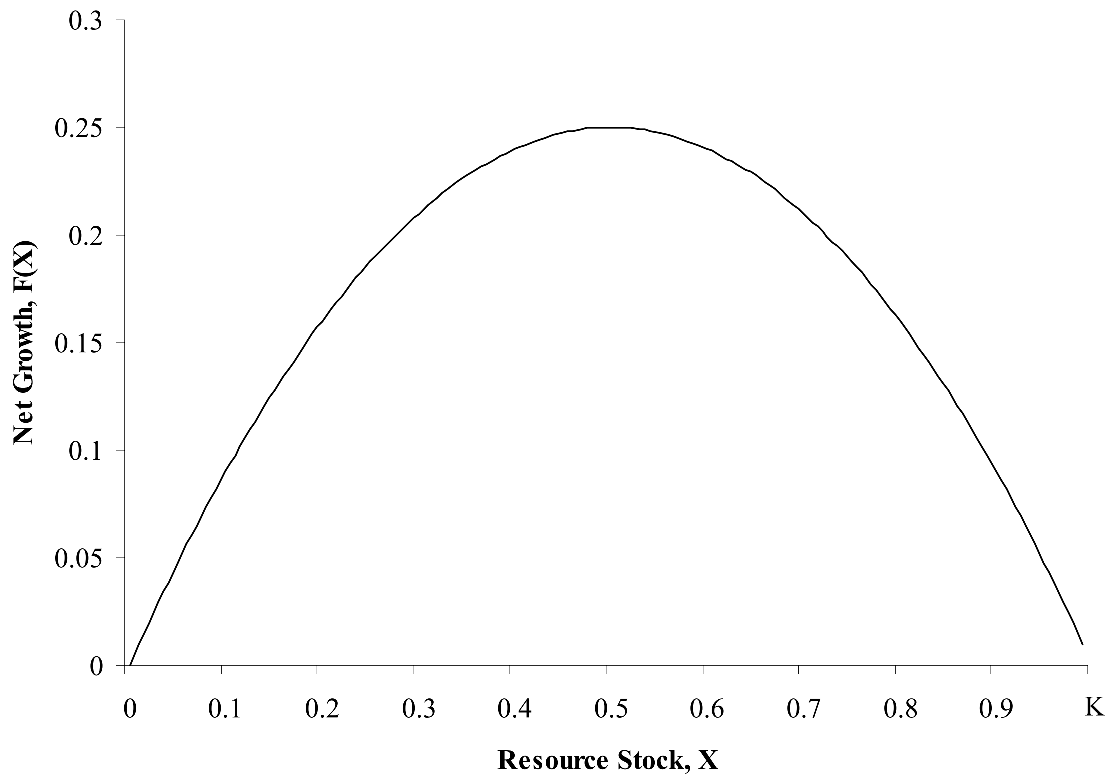

Figure 1. Theoretical Logistic Net Growth Function of a Renewable Resource

Harvest (Y_t) can be specified as the choice variable, or itself modeled as a production function subject to technology, effort, and market conditions. For example, in the fisheries literature, it is standard practice to estimate a catchability coefficient (q) to represent technology, and model production as dependent on stock (X_t) and effort (E_t) in a constant returns to scale Cobb-Douglas function:

$$Y_t = H(X_t, E_t) = qX_tE_t \quad (3)$$

Effort, in turn, can be modeled as a function of profitability:

$$E_{t+1} = E_t + \eta[pH(X_t, E_t) - cE_t] \tag{4}$$

where $\eta > 0$ represents the speed to which effort adjusts to profit, p captures the price per unit of harvest, and c equals the cost per unit effort.

The allocation decision in this framework is a balance (or marginal trade-off) between the net benefits of more Y_t in the current period or more X_{t+1} in the next period, the source of future growth and benefits. Larger future stocks can also have the added benefit of reducing future harvest costs.

By specifying a net benefit function, $\Pi(X, Y)$, and a discount rate, δ, methods of dynamic optimization can be used to estimate specific optimal time paths of effort, harvest, and resource stock. A number of methods exist for this purpose, with marginal valuation and discounting common to each.

2.1. Fundamental Equation of Renewable Resources

To illustrate the economic intuition characteristic of this class of resource allocation problems, consider the conditions for optimal management of a renewable resource in steady-state. Analytically, the time subscript can be dropped in order to solve for steady-state levels of X and Y. By specifying a net benefit function $\Pi(X, Y)$ dependent on both steady-state stock size and harvest level, a discount rate (δ), and resource dynamics according to equation (1), the following two conditions must hold in an optimal steady-state:

$$Y = F(X) \tag{5}$$

$$F'(X) + \frac{\partial\Pi(X,Y)/\partial X}{\partial\Pi(X,Y)/\partial Y} = \delta \tag{6}$$

The first condition is obvious; harvest must equal growth at a steady-state point. The second condition, know in the literature as the fundamental equation of renewable resources, illustrates the economic logic common to classical resource economics. The left-hand side includes two terms. The first term, the total derivative of the growth function, captures the marginal addition to the net growth rate in the steady-state. The second term is the ratio of partial derivatives of the net benefit function with respect to stock in the numerator and harvest in the denominator. Known as the marginal stock effect, this term measures the marginal value of X relative to Y. Together, the left-hand side of equation (6) captures the internal rate of return of the resource at steady-state. At a steady-state optimum, equation (6) implies that this internal rate of return must be exactly equal to the opportunity cost of managing the resource (i.e. the discount rate).

The logic follows that an investor in a renewable resource will continue to harvest and draw down a resource stock so long as its internal rate of return is greater than what she could receive in return on her next best investment alternative. If this marginal return falls below what could be made by liquidating assets and investing in an alternative investment with a certain return of

δ, then the investor should decrease harvest in the short-run and restore the equilibrium condition where marginal benefits equal marginal costs, or exit the industry in the long-run. Figure 1 represents a locus of points where $Y = F(X)$, ranging from $X = 0$ (extinction), $X = 0.5$ (maximum sustainable yield) to $X = K = 1$ (carrying capacity). With the condition implied by equation (6), a steady-state optimum can result in high ($X > 0.5$), low ($X < 0.5$), or extinct resource levels, depending on the various bioeconomic parameters specified. For instance, Colin Clark has used this framework to demonstrate that driving an animal species to extinction can be a market optimum.

2.2. Application: Open Access Fishery

The steady-state satisfying equations (5) and (6) is often considered the bioeconomic optimum, denoted as X*, E*, and Y*. In a fishery, this long-run optimum is found by maximizing the discounted net present value of the fishing harvest over time, and is often interpreted as the solution to the social planner's problem of welfare maximization. However, this solution presumes clearly defined property rights and control of the fishery resource. In contrast, many fisheries are common property resources. A resource in which little to no property rights exist introduces the issue of open access and the potential result of too much effort chasing too few resources, often referred to as the tragedy of the commons.

To illustrate, consider the dynamic optimization framework developed above at the steady-state open access equilibrium. First substitute the production function of equation (3) for Y_t in equation (1) to describe fishery dynamics in terms of stock and effort. In a steady-state, growth must equal harvest, so this expression can then be solved for X as a function of only effort (E). Substituting this function for X into the Cobb-Douglas production function of equation (3) will then show the steady-state relationship between harvest and fishing effort. For the case of logistic growth, this yield-effort curve (denoted Y(E)) will follow the same shape of Figure 1 with yield on the vertical axis and effort on the horizontal axis. Maximum sustainable effort is the ratio of intrinsic growth over the catchability coefficient (r/q), and maximum sustainable yield is one-fourth of the product of intrinsic growth and carrying capacity (rk/4).

All of the points along the yield-effort curve are candidates for the steady-state solution to the open-access fishery. Without clear property rights or any social norms to protect the fishery, the open access fisher pays no access fees and therefore no user cost. The open access fisher also has no control over the behavior of other fishers since there are no barriers to entry. The individual fisher would act to maximize profits, which in the long-run (or steady-state) would imply a zero economic profit condition, where total private revenues generated in the fishery exactly equal total private costs. Assuming a constant net price for fish (p), revenue is simply price times yield, or pY(E). If cost per unit effort (c) is similarly assumed constant, then the steady-state solution to the open access fishery can be solved for E, Y, and X where $pY(E) = cE$.

The positive steady-state solution to the open access problem is often denoted E_∞, Y_∞, and X_∞ since the same solution can be reached in the limit to the present value maximization problem with an infinite (∞) discount rate. Since any steady-state is interpreted as a long-run solution to a dynamic system, the stability of this point is often explored given an initial condition. Due to system non-linearity, and depending on the values of the various bioeconomic parameters implicit to equations (2), (3), and (4), dynamic approach paths can either converge to the steady-state, demonstrate n-cycle behavior, develop periods of chaos, or show combinations of these three system behaviors. The solution $X_\infty = E_\infty = Y_\infty = 0$ is also a steady-state to which convergence may exist, particularly just past parameter thresholds in some specifications. For example, Figure 2 demonstrates possible approach paths to both positive (denoted with an asterisk) and zero steady-state values of E_∞ and X_∞ in the dynamic open access model described above, with the growth function:

$$F(X_t) = rX_t\left(\frac{X_t}{K_0} - 1\right)\left(1 - \frac{X_t}{K}\right) \quad (7)$$

This logistic-form growth function (called a critical depensation curve) includes a parameter for minimum viable population level (K_0), where $X < K_0$ are stock levels in which natural mortality rates are greater than birth rates and resource extinction is assured. Each of the diagrams of Figure 2 have in common the parameter set $r = 0.1$, $K_0 = 0.1$, $K = 1$, $n=5$, $q = 0.1$, and $p = 1$, and the initial conditions $E_0 = 1$ and $X_0 = 0.6$. The only parameter that varies is cost-per-unit effort (c), resulting in two distinct outcomes. At $c = 0.07$ and 0.06, the system converges both rapidly and slowly to positive steady-states. At $c = 0.05$, the system initially behaves as a limit cycle but eventually crosses the K_0 threshold, forcing convergence to the zero steady-state. At $c = 0.04$, extinction is the clear outcome early in the trajectory ($t > 15$).

The management implications from the economic analysis of fisheries have been a variety of policies that attempt to either constrain system parameters or provide the economic incentives to move the steady-state away from the open access solution and toward the bioeconomic optimum. The constraint (or regulatory) approach has been applied through controlling the length of the fishing season, entry to the fishery, the type of fishing technology, and total allowable catch. The economic framework of marginal valuation, however, views such regulatory measures to be inefficient mechanisms to correct the market failure of open access. In contrast, the economic approach to policy design is to introduce a user cost to the individual fisher (i.e. the unrecovered economic rents of open access) through a market incentive mechanism. Two such mechanisms include a landing tax and individual transferable quotas (ITQs). Both rely on successfully introducing an institutional framework for reporting and capturing these rents, and both are focused on the marginal harvest as the unit of control.

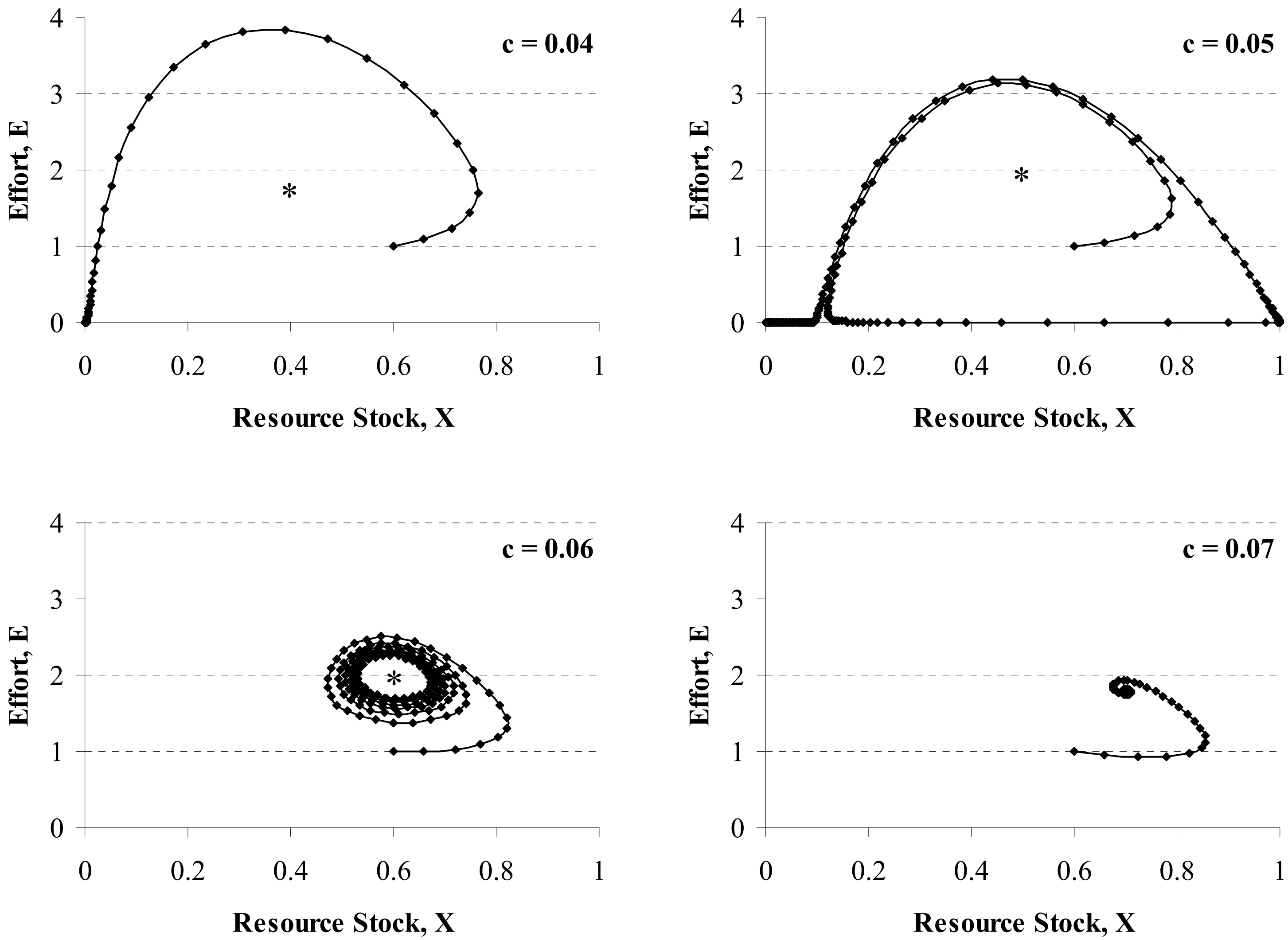

Figure 2. Convergence to Steady-States in an Open Access Fishery Model

3. Investment under Uncertainty

Much of the early literature on the economics of renewable resources was cast in a decision environment of perfect certainty. However, both biological parameters (such as growth rates and carrying capacity) and economic parameters (such as price and marginal costs) are more likely to exhibit stochastic change over time. In addition, the goal of simple net present value maximization (the pre-cursor to equations (5) and (6) in the renewable resource steady-state) may be misplaced when economic activity can be characterized by irreversibility and flexibility in timing. In such applications, a framework of investment under uncertainty is more suitable.

This now popular framework for natural resource valuation and management has generally emerged from theories of capital investment, and more specifically from the options value literature of corporate and public finance. Most decisions to invest exhibit some degree of irreversibility; where initial capital outlays can never be recovered or externalities associated with economic activity can not be reversed. The timing of many investments can also be flexible. Both irreversibility and the ability to wait for new information introduce a positive value of delay to many investments. Known as an option value, this additional opportunity cost of investment can push optimal rates of return well-above discount rates common to the traditional net present value framework. When uncertainty is explicitly considered, stochastic trigger values can be developed that indicate *when* (rather than just *if*) an investment should be undertaken. Such stochastic optimal timing problems have become an important part of the renewable resource economics literature.

3.1. Application: Forest Rotations

The issue of optimal investment timing has received considerable attention in the forest economics literature. The economic question of *when* to harvest a standing forest (i.e. rotation length) has been considered by generations of well-known economists, including Fisher, Boulding, and Samuelson. Economists have considered both the single and infinite rotations problem along many spectrums, from even- to uneven-aged management, homogenous to heterogeneous forest products, pure market to diverse non-market values, and deterministic to stochastic change. The starting point of much of this analysis is the model developed by Martin Faustmann in the 19th century. Faustmann was concerned with estimating the taxable value of land committed to permanent, renewable forest production. Toward this end, he developed a financial model to determine when to harvest an even-aged forest planted on unforested land. Assuming a continuous-time discount factor ($e^{-\delta t}$), continuously twice differentiable merchantable stand value function ($V(t)$), and constant cutting/ replanting cost (c), the Faustmann result to the infinite horizon profit maximization problem is:

$$V'(t) = \delta[V(t) - c] + \frac{\delta[V(t) - c]}{e^{\delta t} - 1} \tag{8}$$

The t^* satisfying this first order condition equates the marginal benefit of waiting to the marginal cost of delaying the current stand (i.e., interest forgone on current net revenue) plus the marginal cost of delaying all future stands (i.e., interest forgone on site value). The logic of equation (8) stems from that of the fundamental equation of renewable resources presented above, and depends on the strong assumption of perfect, continuous, resource renewability. Annual amenity values of the standing forest (i.e. wildlife habitat, watershed protection, scenery, recreation, etc.) have also been added to this framework and typically result in longer rotations then when only merchantable timber values are included. In the case of old-growth forest valuation, amenity values have been argued as being potentially high enough to never cut; an infinite optimal rotation.

With this background, the tree-cutting problem has been an ideal application domain for the investment under uncertainty framework outlined above. Investment timing is clearly the focus of timber management, and can be influenced by the stochastic evolution of timber price, net harvest costs, biological growth, and amenity value. For instance, timber prices have been modeled as stochastic paths with fixed rates of average drift and variance. The general result has been an uncertainty-adjusted discount rate and the estimation of an optimal stopping barrier to stochastic paths of timber value. Following Clarke and Reed, Figure 3 illustrates a time dependent optimal stopping barrier and three sample paths for timber value that could lead to significantly different rotation times (t*).

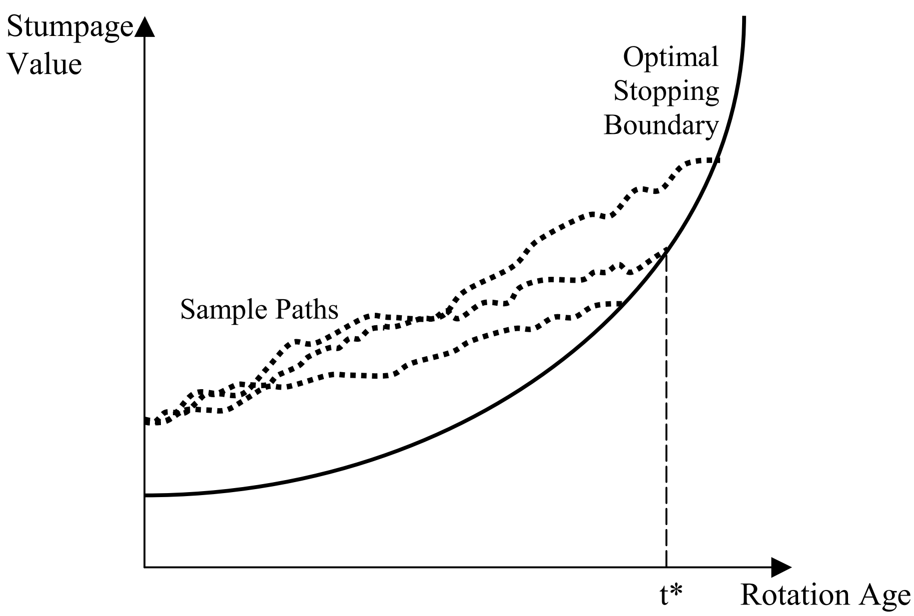

Figure 3. Optimal Stopping Boundary and Sample Stumpage Value Paths

This framework results in an estimate of the economic value to reducing uncertainty. With respect to decisions that could have irreversible consequences, this represents an important augmentation to traditional analysis that places a value on the availability of new information (an option value of delay). With option values included, decisions to harvest or extract a resource may be delayed until new scientific or economic information is obtained. For example, Conrad has demonstrated through an option value model of old-growth forestry that sufficiently high uncertainty over amenity values could result in a decision to avoid irreversibly removing the last remnants of an old-growth ecosystem.

4. Scale, Resilience, and Sustainability

Environmental management based on an optimal control perspective (presented above) has tended to simplify complex systems and devise policies that push systems toward theoretical equilibrium. Modeling stochastic processes and option values is a step toward improving decisions under uncertainty and irreversibility. However, uncertainty in these models ultimately depends on decisions made at the margin in well-behaved representations of change. Benefits to resource preservation and conservation further depend on pricing non-market goods in a marginal benefits equal marginal costs framework. Capturing such complexity through marginal market values (whether uncertainty is explicit or not) has come under fire from those engaged in more interdisciplinary studies of co-evolving, interdependent, socio-ecological renewable resource systems.

In contrast to the optimistic models of the traditional economic approach, a complex adaptive systems view is presented below in which the scale of economic activity, resilience of environmental infrastructure, and sustainability of system boundaries are considered paramount to broader social goals. This view is inherently multidisciplinary, and as such does not easily reduce to a system of equations or decision rules. Rather, a complex adaptive systems view tends to be more retrospective, looking back in time for lessons on how to behave in co-evolving systems. A process-oriented approach – in contrast to the tradition of goal orientation in economics – takes a more prudent stance on human interaction with complex ecosystems and holds a more central concern for sustainability. Here, sustainability is not a question of pushing a system towards a pre-defined steady-state, but rather preserving the underlying conditions for resilience.

4.1 Complex Adaptive Systems Management

The current state of complex adaptive systems theory has been aptly summarized by the final report of the Resilience Project, a three-year, interdisciplinary, international collaboration supported by the MacArthur Foundation (*see* www.resalliance.org/reports/). The Project was designed around two general observations on the socio-ecological dynamics of renewable natural resource systems. First, regional policy is designed to respond to immediate problems and crises, however, over time they lead to agencies that become rigid and myopic, economic sectors that become dependent, ecosystems that become more fragile, and a public that loses trust in governance. Optimal, marginal management is seen as contributing to this fragility. Second, the great complexity, diversity, and opportunity in complex regional systems emerge from a handful of critical variables and processes that operate over distinctly different scales in space and time. Optimal, marginal management has tended to focus only on "fast" variables that change over economic planning horizons, missing longer term signals of reduced resilience.

C.S. Holling and his colleagues proposed a framework to explain such transitions in behavior in complex systems as an evolutionary path through four common stages. Figure 4 characterizes Holling's Adaptive Cycle, which has been extended in the work of the Resilience Alliance and elsewhere to interdependent social and ecological systems. The central idea is that renewable resource systems will be characterized by patterns of growth and exploitation of natural capital and by increasing connectedness among their components. Starting in the *Growth* stage (SW quadrant of Figure 4) and moving toward the *Conservation* stage, r-selected species that tend to overshoot and collapse will be replaced by K-selected species that are constrained by the system's carrying-capacity. During the *Conservation* stage, the greater exploitation of natural capital leads to a strong degree of system connectedness and fragility, followed by an eventual release of stored capital and system *Reorganization*. The fall from K to α can result from a threshold response from either accumulated or spasmodic perturbation. Holling argues that in the *Reorganization* stage the system is most likely to be transformed by innovation, i.e. when economic agents have the greatest potential to influence the future of the system (i.e. adaptive behavior). In Figure 4, the arrows show the speed of change in the ecosystem cycle, with periods of many arrows representing long adjustment, and periods of one or few arrows indicating relatively rapid system changes. An exit (or system flip) from the cycle can also occur, typically between *Reorganization* and *Growth*, into either a less or more productive and organized system. A third dimension to this figure would be resilience, where system resilience would be shown to fluctuate throughout the adaptive cycle, for instance contracting during the *Conservation* stage and expanding during the backloop from *Release* to *Reorganization*.

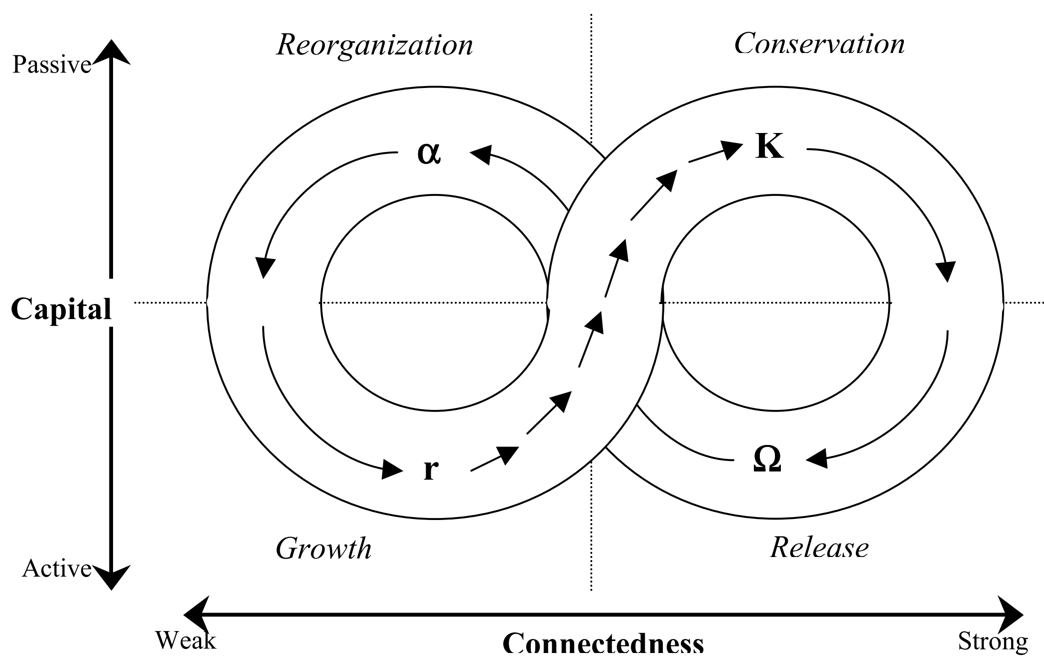

Figure 4. Adaptive System Cycle

Several general hypotheses have emerged from the study of complex adaptive systems. The 2000 report of the Resilience Project identifies the following: (i) abrupt shifts among a multiplicity of very different stable domains are plausible in regional ecosystems; (ii) an adaptive cycle that alternates between long periods of aggregation and transformation of resources and shorter periods that create opportunities for innovation, is the fundamental unit for understanding complex systems from cells to ecosystems to societies; (iii) exceptions to the adaptive cycle include (among others) ecosystems strongly influence by episodic inputs with little internal regulation and highly adaptive responses to opportunity; (iv) sustainability is maintained by relationships amongst nested adaptive cycles arranged across a hierarchy of space and time; (v) discontinuities and abrupt change will effect nested adaptive cycles at varying scales and provide for the opportunity to reorganize freed up resources; (vi) learning and institutional change can be incremental, spasmodic, or evolutionary, depending on how learning is influenced by the speed and connectedness of system dynamics; (vii) integrated systems exhibit emergent behavior if they have strong connectivity between the human and ecological components; and (viii) non-linearities and uncertainty can make traditional optimization impossible and active adaptive management necessary.

4.2 Application: Lake Management

Collaborations of natural and social scientists have led to innovative models of Holling's Adaptive Cycle. The study of lake systems is one example that has culminated into computer model exercises that exhibit patterns resembling the cycle and stages depicted in Figure 4. For example, Steve Carpenter of the University of Wisconsin and his colleagues built an interacting-agent model of a lake watershed economy subject to phosphorus pollution from agriculture. The general pattern begins during the exploitation phase of Figure 4 (from r to K), as the proportion of phosphorus-intensive farms increases and the ecosystem becomes more fragile due to upland soil and lake mud accumulation. Eventually, the system is perturbed away from this economically desirable path, and phosphorus levels in the water move rapidly to a polluted state. In the agent-based model, a lake manager attempts to avoid disaster by reducing the proportion of phosphorus-intensive farms, however the high levels of phosphorus in the system can make eutrophication inevitable, leading to collapse (from K to Ω). As social institutions adjust with massive changes to farm policy, a drastic reduction in the proportion of phosphorus-intensive farms leads to gradual reductions in phosphorus levels in soil, mud, and lake water (from Ω to α). This *Reorganization* phase eventually leads to a low phosphorus condition that initiated earlier dynamics and, absent of an exit into a new system, a new phase of exploitation can begin.

This example highlights two key features of the adaptive management literature: (i) a careful distinction between the speed of different socioeconomic and ecosystem processes, and (ii) the incorporation of learning and adaptation by heterogeneous agents. First, consider the issue of variable speed, illustrated by Figure 5. In the example of lake eutrophication, phosphorus levels in the water may be considered a fast variable (x-axis) amenable to monitoring and incremental management. Phosphorus accumulation in lake sediment or upland soils (y-axis) is a much slower variable, often ignored by policy makers since it has limited impact on surface water quality of a typical time period and can be very expensive to monitor. If the watershed economy is currently at a desirable state (denoted by the asterisk in Figure 5) individual agents may continue to increase phosphorus levels in the water in accordance with a marginal net benefit valuation. An economy may even opt for a technological fix focused on the fast variable, for instance, by lowering phosphorus levels before water consumption. However, the slow accumulation of sediment and soil phosphorus may eventually result in a discontinuous, episodic surprise (for instance, a storm event) that moves the system into an undesirable state of high levels of phosphorus in surface water, perhaps leading to severe eutrophication.

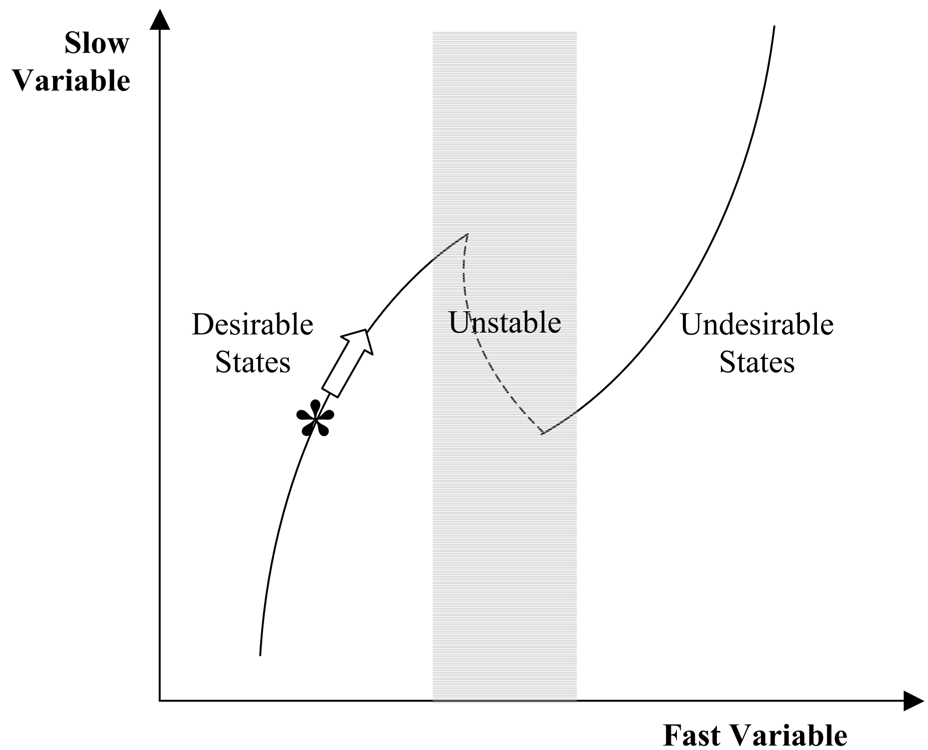

Figure 5. Discontinuity and Surprise in a Watershed Economy

The second feature of an adaptive systems approach is the use of heterogeneous agents in adaptive decision-making. Agent-based modeling is a methodology of much recent research in economics and the study of complexity in general. Their central feature is multiple decision-makers (or agents), each with their own set of beliefs, immediate behaviors, and rates of learning. In contrast to the dynamic optimization models in which the decision process is structured around one social planner with perfect foresight, agent-based models most often result in disequilibrium behavior and, at times, emergent properties. Models are not meant to be predictive, but rather exploratory and useful by the actual participants of the decision-making process to judge potential long-run consequences of the accumulation of short-term decisions. For example, the Carpenter et al. lake model explores different decision making frameworks, ranging from dominant individual decisions (the Market Manager model) to competing interests in a political decision process (the Governing Board model) to decisions of a social planner (the Land Manager model).

Non-point source pollution from agriculture is just one of many perturbations to co-evolving watershed economies. Other sources of impact include leaky residential septic systems, draining and development of wetlands, removal of riparian vegetation, introduction and spread of exotic species, and overfishing. All represent large-scale system changes that can move the system closer to flipping into undesirable states. The typical policy response is reactive in nature, responding to changes only in fast variables, and often missing clues of general loss of resilience. In contrast, an adaptive systems management approach attempts to control system parameters so it can self-regulate within the boundaries of resilience around a desirable state. It is not equilibrium-oriented in the sense of moving the system to the point estimate of a steady-state, but rather seeks to remain in the basin of attraction of a broadly-defined desirable state. It is not margin-oriented in the sense of adopting policies to influence incremental decision-making, but rather takes a scale-oriented approach to policy design. And lastly, adaptive systems management does not operate solely on short-term time horizons, but rather focuses on long-term system maintenance toward achieving goals of sustainability.

5. Concluding Remarks

Evidence of worldwide renewable resource decline is apparent along both socioeconomic and ecological gradients. Statistics on ocean fishery depletion, forest land conversion, topsoil loss, desertification, species extinction, and freshwater diminution, overwhelmingly point to the consequences of human domination of the planet's resources. This data has most often been presented as smooth, continuous trends. However, perhaps most striking is recent research on catastrophic shifts in entire ecosystem types. An October 2001 article in *Nature* (Vol. 413, pp. 591-596) presents evidence of dramatic flips in state apparent in lake, coral reef, woodland, desert, and ocean systems resulting from continuous, incremental pressure.

Optimal control theory, as presented in Section 2, has been the dominant 20th century paradigm behind the analysis of and policy advice in renewable resource systems. At the dawn of the 21st century and in the wake of worldwide renewable resource decline, policy-makers and resource economists alike are in search of a broader, more holistic view of complex and interdependent socio-ecological systems. Many have taken an approach of improving upon the old framework, as evident by the option value approach presented in Section 3. Others have looked beyond traditional disciplinary walls for entirely different perspectives on renewable resource management, for instance, the complex adaptive systems approach presented in Section 4.

Neither discussion above is meant to be an exhaustive treatment of an economic nor natural science based approach to renewable resource systems, but rather highlights the key differences in foundation. Most dramatic is the seemingly polar extremes of the economist's focus on efficiency and the natural scientist's focus on resilience. At the heart of nearly all economic models of renewable resources is the goal of efficiency, where marginal benefits of the next resource put to economic use is exactly equal to its marginal cost of production and/or to society. This approach has been successful in generating maximum short-run returns to capital investment, however, has failed to consider the importance of scale and the consequences of unpredictable discontinuous change. Socio-ecological complexity is just simply too overwhelming to manage at the margin. A focus on resilience, in contrast, could help define the boundaries of the system in which economic actors can then go about the calculus of maximization.

Bibliography

Brown, G.M. (2001). Renewable natural resource management and use without markets. Journal of Economic Literature 38, 875-914. [A recent review of the core of renewable resource economics].

Carpenter, S., W. Brock and P. Hanson (1999). Ecological and social dynamics in simple models of ecosystem management. Conservation Ecology 3(2), 4. [Outlines the agent-based model of lake eutrophication discussed in section 4.2; available online at www.consecol.org/vol3/iss2/art4].

Clark, C.W. (1973). Profit maximization and the extinction of animal species. Journal of Political Economy 81, 50–961. [Demonstrates using standard assumptions of market behavior that a species can be driven to optimal extinction].

Clark, C.W. (1990). Mathematical Bioeconomics: the Optimal Management of Renewable Resources, 386 pp. New York, NY, USA: John Wiley & Sons, Inc. [A hallmark text on the dynamic optimization approach to renewable resource economics].

Clarke, H.R. and W.J. Reed (1989). The tree-cutting problem in a stochastic environment: the case of age-dependent growth. Journal of Economic Dynamics and Control 13, 569-595. [Demonstrates the application of an option value approach to the tree-cutting problem discussed in section 3.1].

Conrad, J. (1999). Resource Economics, 213 pp. Cambridge, UK: Cambridge University Press. [An excellent introduction to classical resource economics, with ample opportunity to learn the material through spreadsheet-based applications. Section 2 follows closely the exposition of dynamic optimization presented in this resource].

Dixit and Pindyck (1994). Investment under Uncertainty. Princeton, NJ, USA: Princeton University Press. [The benchmark resource for the option value approach to investment analysis].

Gunderson, L.H., C.S. Holling and S.S. Light (eds.) (1995). Barriers and Bridges to the Renewal of Ecosystems and Institutions. New York, NY, USA: Columbia University Press. [A thorough summary of the theory and application of an adaptive systems management approach to renewable resources].

Holling, C.S., C. Folke, L. Gunderson and K.G. Maler (2000). Resilience of ecosystems, economic systems, and institutions. Final Report submitted to the John D. and Catherine T. MacArthur Foundation, April 30. [A recent, broadly accessible summary of the adaptive systems management approach; available online at www.resalliance.org/reports/].

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke and B. Walker (2001). Catastrophic shifts in ecosystems. Nature 413, 591-596. [Summarizes the current theory behind and evidence of flips in states of various ecosystem types around the world].