RENEWABLE RESOURCE MANAGEMENT

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Contents

Summary

The management of renewable resources can be viewed as a dynamic allocation problem. How much of a resource should be harvested today and how much should be left for tomorrow? Models of resource management might partition time into discrete, uniform intervals (for example, years), or they may treat time as continuous. Resource growth might be deterministic or stochastic (where a random variable or process influences the evolution of the resource stock). This essay looks at the four types of renewable resource models that might result from discrete- or continuous-time coupled with deterministic or stochastic dynamics. After presenting four reasonably general models, six specific models, applied to fishery, forest, and groundwater resources, are presented. The Method of Lagrange Multipliers, the Maximum Principle, and Dynamic Programming are used to determine optimal allocation or the form of an optimal, adaptive policy. The four general models and the six specific models were designed to

give the reader all the necessary theory and methods to confidently approach the large and growing literature on the economics of renewable resources. In the process of working through these models, the reader should also gain an understanding of steady-state equilibria in deterministic models and adaptive policies and stationary distributions in stochastic models, and how these concepts might relate to the often ill-defined term, "sustainable resource use." The essay concludes with a discussion of some of the impediments to improved resource management, the information needed to estimate the parameters of renewable resource models, and the institutions that might be needed to improve the allocation of fishery, forest, and water resources.

1. Introduction

This essay will present some basic economic models of renewable resources. A renewable resource is one that exhibits significant growth or renewal over an economic horizon. Most plant and animal populations would be regarded as renewable resources. The water in a lake, stream, or underground aquifer, if replenished through a cycle of evaporation and precipitation, might also be regarded as a renewable resource. If, however, a resource has a very small rate of growth or renewal, it might be more appropriate, from an economic perspective, to regard it as a nonrenewable resource. For example, the remaining stands of old-growth coast redwood (*Sequoia sempervirens*), found in California, may be 1000 years old or older. While redwoods can be cultivated, the length of time to achieve old-growth status may be so long, relative to most economic planning horizons, that these majestic trees are best regarded as a nonrenewable resource. Similarly, some aquifers have such a small rate of recharge that they are more like an underground pool of oil, and thus more appropriately modeled as a nonrenewable resource. Because renewable resources exhibit a significant rate of growth or renewal they would seem good candidates for sustainable harvest. The definition of sustainability is problematic. This is particularly the case if we admit that the rate of growth or renewal for a resource fluctuates through time. Indeed, the process of evolution raises some fundamental questions about the feasibility of sustainable resource use.

The remainder of this introductory section will present the components of the basic bioeconomic model. The subsection on resource dynamics will introduce the distinction between continuous- and discrete-time models as well as deterministic and stochastic models. The second subsection formulates general objectives for resource management within a deterministic and stochastic environment. The third subsection discusses sustainability and adaptive management. Section 2 will assemble the components from subsections 1.1 and 1.2 and present four bioeconomic models.

Section 3 contains six models of fishery, forest, and groundwater resources. These models are special cases of the more general models of Section 2. These models give further insight into the basic problem of resource management. Section 4 concludes with a discussion of the practicality of these models and the impediments to improved resource management in the real world.

1.1 Resource Dynamics

Resource economics is concerned with how natural resources are allocated over time. The stock of a renewable resource will change with net natural growth and harvest. The change in a resource stock might be modeled using a differential or difference equation. Let X_t denote the stock of a renewable resource at instant t and $X_{t+\Delta t}$ the stock at instant t+Δt, where we initially assume Δt is some small but positive increment of time. Suppose over the interval Δt that the net natural rate of growth is given by the function $F(X_t)$ and that the level of harvest is denoted by $Y_t \geq 0$. Assume that X_t, $F(X_t)$ and Y_t are all measured in the same units. (In the models of this essay we will assume that the mass or volume of a resource stock can be measured, for example metric tons of herring, cubic meters of wood, or gallons of water.) Then the rate of change in the resource, going from t to t+Δt, may be calculated according to

$$\frac{X_{t+\Delta t} - X_t}{\Delta t} = F(X_t) - Y_t \tag{1}$$

If time is continuous we can let $\Delta t \to 0$ and equation (1) becomes a differential equation that is often written as

$$\dot{X} = F(X) - Y \tag{2}$$

where $\dot{X}$ = dX/dt denotes the time rate of change in the resource and X and Y are the resource stock and level of harvest at instant t, respectively. Alternatively, if Δt = 1 equation (1) becomes the first-order difference equation

$$X_{t+1} - X_t = F(X_t) - Y_t \tag{3}$$

Equation (3) is often written in iterative form as

$$X_{t+1} = X_t + F(X_t) - Y_t = G(X_t, Y_t) \tag{4}$$

If X_0 and Y_0 are known then $X_1 = G(X_0,Y_0)$. If Y_1 is known then $X_2 = G(X_1,Y_1)$, and one could simulate the dynamics of the stock for a known or candidate harvest schedule, Y_t, from the initial condition, X_0. Modern spreadsheet software makes such simulations relatively easy to do.

A stochastic or fluctuating environment may make growth, and thus the stock in period t+1, a random variable. Suppose z_{t+1} is a random variable, perhaps water temperature that influences the growth of a fish stock. The realized value for z_{t+1} can only be observed at the beginning of t+1. The value of X_{t+1} is determined by

$$X_{t+1} = G(X_t, Y_t; z_{t+1}) \tag{5}$$

Suppose in period t we can observe or accurately measure X_t. While X_t is observable, the consequences of Y_t on X_{t+1} cannot be known with certainty in period t, when a decision on the level of Y_t must be made. It is usually assumed that the random variables, z_{t+1}, are independent and identically distributed (i.i.d.), being generated by the density function $f(z_{t+1})$.

Stochastic differential equations are also used in modeling the dynamics of natural resources. In such models the resource stock becomes an *Itô variable* with dynamics described by

$$dX = [F(X) - Y]dt + \sigma(X)dz \qquad (6)$$

The first term on the right-hand-side of (6) is called the mean or expected drift rate. It depends on the relative rates for net growth and harvest, as in the ordinary differential equation, (2). The term $\sigma(X) > 0$ is the standard deviation rate, and $dz = \varepsilon(t)\sqrt{dt}$ is the increment of a *Wiener process,* where $\varepsilon(t)$ is a standard normal random variable, $\varepsilon(t) \sim N(0, 1)$. In Sections 2 and 3 of this essay we will consider dynamic optimization problems based on the above equations for deterministic and stochastic growth. The deterministic models are generally more tractable and might be solved using the Method of LaGrange Multipliers, the Calculus of Variations, or the Maximum Principle. Problems with stochastic growth [equations (5) and (6)] will typically employ Dynamic Programming to find an optimal harvest policy.

1.2 Management Objectives

A well-defined resource management problem needs a clear objective. There are many potential objectives. A reasonably general approach is to define $\pi_t = \pi(X_t, Y_t)$ to be the net benefits at instant or period t from having a resource stock of size X_t and harvest at rate Y_t. In continuous-time models, this objective is often written as $\pi = \pi(X,Y)$, with the presumption that π, X, and Y are all measured at instant t.

It is possible that net benefits might only depend on the rate of harvest, in which case $\pi = \pi(Y)$. Dependence of net benefits on the resource stock can arise for at least two reasons. First, in a strictly commercial setting, the cost of harvesting Y at instant t may depend on the size of the stock at instant t. It is the case for many resources that the larger the stock, the lower the cost for any level of harvest. Second, for certain animals, most notably marine mammals, the stock may convey "non-consumption" benefits associated with wildlife observation. The larger the stock of, say, humpback whales, the more likely they will be seen by humans on a "whale-watch cruise." For certain species, humans may derive an "existence value" simply knowing that the population still exists in the wild. Larger populations may mean the species is more secure, and existence benefits may be higher.

Underlying $\pi = \pi(X, Y)$ is the presumption that "economic man is the measure of all value." Such a perspective does not prevent *homo economicus* from having environmental and conservation motives. To determine their importance, non-consumptive benefits must be estimated, in a dollar metric, so that the value of a larger stock in the future can be compared with the increment in benefits that might be obtained from a larger harvest today. This cuts to the heart of resource management; the need determine the “best” harvest schedule from many feasible schedules. Different harvest schedules will have different implications for resource dynamics and the future flow of net benefits. Calculating the present value of net benefits is one way to rank or evaluate alternative harvest schedules. In continuous time the present value, PV, of net benefits from a harvest schedule, Y, that induces the resource trajectory, X, over an infinite horizon is given by

$$PV = \int_0^\infty \pi(X,Y)e^{-\delta t}dt \tag{7}$$

where $e^{-\delta t}$ is the continuous-time discount factor and $\delta > 0$ is the instantaneous rate of discount. A common objective in bioeconomics is to maximize the present value of net benefits with respect to the harvest schedule, Y, for $\infty > t \geq 0$.

In discrete time, where the net benefits in period t are $\pi_t = \pi(X_t,Y_t)$, the present value of net benefits is written as

$$PV = \sum_{t=0}^{\infty} \rho^t \pi(X_t,Y_t) \tag{8}$$

where $\rho = 1/(1 + \delta)$ is the discrete-time discount factor and δ is now the periodic rate of discount.

As in continuous time, a common objective is to maximize PV by choosing $Y_t \geq 0$ for t = 0, 1, 2, ... , ∞. When growth is stochastic the objective of resource management is often the maximization of expected present value. Dynamic programming is used to find a value function that gives the expected present value in period t from having a stock of size X_t, assuming that the resource is optimally harvested in the future. The value function, $V_t(X_t)$ must satisfy a recursive equation, called the *Bellman equation,* which takes the form

$$V_t(X_t) = Max[\pi(X_t,Y_t) + \rho E_t\{V_{t+1}(G(X_t,Y_t;z_{t+1}))\}] \tag{9}$$

where $E_t\{\bullet\}$ is the expectation operator in period t and the maximization of $[\bullet]$ is with respect to Y_t. The value function, $V_t(X_t)$ requires that Y_t be chosen so as to maximize the sum of current net benefits, $\pi(\bullet)$, plus the discounted expected value of having a stock size of $X_{t+1} = G(X_t,Y_t;z_{t+1})$ in period t+1. If X_t and Y_t are continuous variables, if $\pi(\bullet)$, $V_{t+1}(\bullet)$ and $G(\bullet)$ are concave, differentiable functions, and if the expectation operation is well defined, then the maximal condition requires $\partial[\bullet]/\partial Y_t = 0$, or

$$\partial\pi(\bullet)/\partial Y_t + \rho\,\partial E_t\{V_{t+1}(G(X_t,Y_t;z_{t+1}))\}/\partial Y_t = 0 \tag{10}$$

Equation (10) is a single equation in X_t and Y_t and will imply the optimal feedback policy

$$Y_t^* = \phi_t(X_t) \tag{11}$$

In many infinite-horizon problems the value function and optimal harvest policy are stationary, meaning that they don't depend on time. In this case $Y_t^* = \phi(X_t)$ and the maximized expected present value of having a stock of size X_t is

$$V(X_t) = \pi(X_t, \phi(X_t)) + \rho E_t\{V(G(X_t, \phi(X_t); z_{t+1}))\} \tag{12}$$

where substitution of the optimal feedback policy has accomplished the maximization required in expression (9) and the expectation operator will "integrate out" z_{t+1}, leaving $V(X_t)$.

To summarize, given forms for $\pi(X_t,Y_t)$, $G(X_t,Y_t;z_{t+1})$, the probability density $f(z_{t+1})$, and the discount factor $\rho = 1/(1 + \delta)$, dynamic programming is used in an attempt to find the value function, $V_t(X_t)$ and the feedback or adaptive harvest policy, $Y_t^* = \phi_t(X_t)$, that will maximize the expected present value of net benefits.

1.3 Sustainability and Adaptive Management

The management of a renewable resource in a deterministic environment might result in a steady-state equilibrium where $X_t = X_{t+1} = X \geq 0$ and $Y_t = Y_{t+1} = Y \geq 0$. The steady-state equilibrium, (X,Y), is also called a fixed point, since it is a point in X-Y space which will perpetuate itself. In the continuous- or discrete-time equations for resource dynamics [equations (2) and (3)] a steady state equilibrium must satisfy Y = F(X). In words, a steady state is characterized by harvest equaling net growth. This makes intuitive sense, since, when harvest equals net growth, stock is unchanging. The net growth function is often specified so that $F(X) > 0$ for $0 < k < X < K$, with $F'(X) > 0$ for $k \leq X < X_{msy}$ and $F'(X) < 0$ for $X_{msy} < X \leq K$, where X_{msy} is the stock size where F(X) reaches a maximum and $Y_{msy} = F(X_{msy})$ is the maximum sustainable yield. A net growth function with these attributes is the cubic function

$$Y = F(X) = rX(X/k-1)(1-X/K) \tag{13}$$

shown in Figure 1, where r = 1, k = 0.25, K = 1, and it can be shown that X_{msy}=0.717.

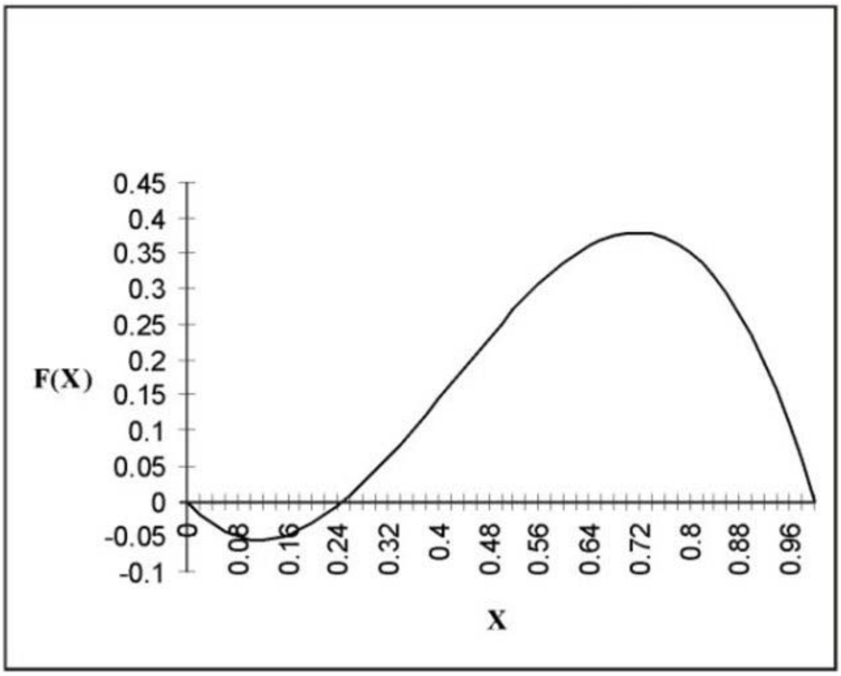

Figure 1. $F(X) = rX(X/k - 1)(1 - X/K)$, $r = 1$, $k = 0.25$, $K = 1$

For the net growth function in Figure 1, $r > 0$ is called the intrinsic growth rate, $k > 0$ is called the minimum viable population, and $K > 0$ is called the environmental carrying capacity.

For $k < X < K$, any point on the net growth function, $F(X)$, is a steady state, and therefore an equilibrium which can support a sustainable harvest $Y = F(X) > 0$. To identify a preferred steady state equilibrium will required the specification of an objective which can be used to rank the infinite number of combinations (X, Y) that would support a sustainable harvest. Depending on management objectives, the preferred steady state might be at a stock size greater than or less than X_{msy}.

In some deterministic models and almost all stochastic models, a sustainable harvest, where $Y_t = Y > 0$, will not be desirable. For stochastic models, where the stock is an induced random variable, a constant harvest policy is not optimal. Intuitively, if the stock is being bounced around by stochastic environmental factors, you would wish to harvest it in an adaptive way, where it is optimal to harvest more of a resource in a year when growth was greater than expected, and less in a year when growth was less than expected.

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Bibliography

Brander J. A. and Taylor M. S. (1998). The simple economics of Easter Island: A Ricardo–Malthus model of renewable use. *American Economic Review* **88**, 119–138. [This paper uses a model similar to (D3) to describe the dynamics of the human population and the resource base on Easter Island.]

Brown G. B. (1974). An optimal program for managing common property resources with congestion externalities. *Journal of Political Economy* **82**, 163–174. [Taxes on harvest and effort are shown to correct overharvesting and congestion in an open access fishery.]

Clark C. W. (1990). *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. 386 pp. New York: John Wiley and Sons, Inc. [The classic reference on bioeconomics.]

Clarke H. R. and Reed W. J. (1989). The tree-cutting problem in a stochastic environment: The case of age-dependent growth. *Journal of Economic Dynamics and Control* **13,** 569–595. [Determines the optimal rotation when timber prices and merchantable volume evolve stochastically, as in Subsection 3.4.]

Conrad J. M. (1999). *Resource Economics*. 213 pp. New York: Cambridge University Press. [An intermediate text using calculus and spreadsheets to solve dynamic resource allocation problems.]

Conrad J. M. and Clark C. W. (1987). *Natural Resource Economics: Notes and Problems*. 231 pp. New York: Cambridge University Press. [A graduate-level text presenting theory, methods, and numerical problems for renewable and nonrenewable resources.]

Dixit A. K. and Pindyck R. S. (1994). *Investment Under Uncertainty*. 468 pp. New Jersey: Princeton University Press. [A highly readable text dealing with the timing and value of investments which are irreversible (or costly to reverse) and risky.]

Faustmann M. (1849). Berechnung des wertes welchen waldboden sowie noch nicht haubare holzbestände für die waldwirtschaft besitzen. *Allgemeine Forst und Jagd-Zeitung* **25**, 441–455. [A nineteenth century German forester correctly solves the infinite-rotation problem. The paper was essentially lost to the economics profession until it was rediscovered in the late 1950s.]

Gordon H. S. (1954). The economic theory of a common property resource: the fishery. *Journal of Political Economy* **62**, 124–142. [A classic paper on the economic incentive to harvest a common property resource to a level where net revenue (or rent) is zero.]

Grafton R. Q. (1996). Individual transferable quotas: theory and practice. *Reviews in Fish Biology and Fisheries* **6**, 5–20. [An accessible paper on the theory of ITQs and their application to fisheries management in Australia, Canada, Iceland, and New Zealand.]

Homans F. R. and Wilen J. E. (1997). A model of regulated open access resource use. *Journal of Environmental Economics and Management* **32**, 1–21. [The authors develop a model of regulated open access where aggregate harvest is limited by a quota. Fishers choose the level of effort and affect season length. Regulated open access can lead to short, intense seasons, with a large volume of fish flooding the market during the season. The model is applied to the halibut fishery in the North Pacific.]

Jaquette D. L. (1972). A discrete time population control model. *Mathematical Biosciences* **15,** 231–252. [A discrete-time stochastic model is developed where if $X_t > X^*$ it is optimal to harvest the stock back down to X^*. If X_t is less than X^*, no harvest takes place.]

Kamien M. I. and Schwartz N. L. (1991). *Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management*. 377 pp. Amsterdam: North Holland. [A graduate-level text dealing with the application of dynamic optimization techniques to problems in economics and management.]

Léonard D. and Long N. V. (1992). *Optimal Control Theory and Static Optimization in Economics*. 353 pp. New York: Cambridge University Press. [A popular, and less pricey, graduate-level text on static and dynamic optimization problems in economics.]

Merton R. C. (1975). An asymptotic theory of growth under uncertainty. *Review of Economic Studies* **42**, 375–394. [Derives the distribution for a stochastically evolving stock when managed using a stationary, feedback policy.]

Pindyck R. S. (1980). Uncertainty and exhaustible resource markets. *Journal of Political Economy* **88**, 1203–1225. [Examines the effects of continuous uncertainty in reserves on the price and rate of extraction of a nonrenewable resource.]

Pindyck R. S. (1984). Uncertainty in the theory of renewable resource markets. *Review of Economic Studies* **51**, 289–303. [A companion paper to the above paper on nonrenewable resources. The special case in Subsection 3.6 comes from this paper.]

Pindyck R. S. (1991). Irreversibility, uncertainty, and investment. *Journal of Economic Literature* **29**, 1110–1152. [A nice survey with a short appendix on Wiener processes, Itô variables, and stochastic dynamic programming.]

Reed W. J. (1979). Optimal escapement levels in stochastic and deterministic harvesting models. *Journal of Environmental Economics and Management* **6**, 350–363. [This paper builds on Jaquette and provides the basis for the discrete-time stochastic model in Subsection 3.5.]

Reed W. J. and Clarke H. R. (1990). Harvest decisions and asset valuation for biological resources exhibiting size-dependent stochastic growth. *International Economic Review* **31**, 147–169. [A more complex paper dealing with size-dependent stochastic growth.]

Schaefer M. B. (1957). Some considerations of population dynamics and economics in relation to the management of marine fisheries. *Journal of the Fisheries Research Board of Canada* **14,** 669–681. [One of the first studies linking biology and economics in the formulation of policies to manage a fishery.]

Sethi R. and Somanathan E. (1996). The evolution of social norms in common property resource use." *American Economic Review* **86**, 766–788. [Shows the tenuous possibility of an equilibrium for a common property resource and a small static community where the resource is *not* over-exploited. Such equilibria are likely to be fragile.]

Tietenberg T. (1998). *Environmental Economics and Policy*. 460 pp. Reading, MA: Addison-Wesley. [A well-written and popular introductory text.]

Biographical Sketch

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