A Dynamic and Stochastic Perspective on the Role of Time in Range Management

by

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Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Montreal, Canada, July 27-30, 2003

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Abstract: This chapter uses a new ecological-economic approach to analyze the role of time in range management in a dynamic and stochastic setting. We first construct a theoretical model of a parcel of rangeland in which time restrictions are used to manage the land. We then show how the dynamic and the stochastic properties of this rangeland can be used to construct two managerial objectives that are ecologically and economically meaningful. Finally, using these two objectives, we discuss an approach to range management in which the manager has two interrelated goals. This manager maximizes the profits from range operations and (s)he also takes steps to move the rangeland away from the least desirable state of existence.

Keywords: Ecological-Economic System, Semi-Markov Process, Time Restriction, Uncertainty

1. Introduction

Time restrictions have been used to regulate the activities of productive units in the western world at least since the Fairs and Markets Act of 1448 in England. Since then, time restrictions have been used to limit the number of hours during which shops can remain open and to control other kinds of trading activities. Consider the case of natural resources in contemporary times. Weninger and Strand (1998) have pointed out that recreational and commercial hunters for most game are subject to seasonal restrictions. Moreover, such hunters are commonly required to hunt during daylight hours. Batabyal and Beladi (2002b) have observed that in virtually every state in the USA, sport fishing seasons exist for a whole host of fish species. Commercial fisheries in Canada, the USA, and in western Europe are subject to a variety of time restrictions.[4] This tells us that today, the use of time restrictions for natural resource management is widespread.

Although time restrictions have been and are used to manage natural resources, they have infrequently been used to manage rangelands.[5] In an early contribution, Hormay and Evanko (1958) advocated the need to rest plants from grazing during certain periods of time. However, Hormay and Evanko's ideas did not receive widespread recognition until the emergence of Allan Savory's *Holistic Resource Management* in 1988. In this book and in subsequent work (see Savory and Butterfield (1999)) Savory has forcefully argued in favor of adopting a time based approach to range management. Specifically, he has contended that from a management perspective, it is important to note that overgrazing bears "little relationship to the number of animals but rather to the *time* plants

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4 For additional details on this subject, the reader should consult Karpoff (1987), Hartwick and Olewiler (1998, pp. 152-175), Batabyal (2001a, 2001b), Batabyal and Beladi (2002a, 2002b), and Xu and Batabyal (2002).

5 In the context of rangelands, a time restriction refers to the length of time during which a rangeland is closed to grazing.

[are] exposed to the animals" (Savory and Butterfield, 1999, p. 46, emphasis in original).[6]

Although this view appears to be gaining currency in the range management profession, very little is known about the *theoretical* properties of time based range management regimes. This is largely because there are *no* analyses that provide an integrated ecological-economic perspective on how a time based management regime affects the ecology and the economics of rangelands. Economists have studied the subject of range management in considerable detail.[7] However, these studies have rarely paid any attention to the *ecological* aspects of the management problem or to the use of *time* as a control variable. In general, these studies have focused on the number of animals that maximize an economic objective function such as a rancher's profit function.

Similarly, although there are many ecological studies of range management,[8] these studies have rarely analyzed *time* restrictions and the *economic* effects of such restrictions. As indicated previously, Hormay and Evanko (1958), Savory (1988) and Savory and Butterfield (1998) have discussed some of the pros and cons of a time based approach to range management. However, because this discussion is largely descriptive, very little is known about the *theoretical* properties of time based management regimes. In addition to this, the three studies just mentioned pay scant attention to the economic aspects of range management.

Given this state of affairs, the present chapter has three goals. First, we build a theoretical

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6 Allan Savory's views on grazing have been variously described as short-duration grazing, the Savory grazing method, and as time-controlled grazing. For more on the practical applications of Savory's views, see Savory and Parsons (1980), Savory (1983), and Holechek *et al.* (2001, pp. 269-277)

7 Examples include Huffaker *et al.* (1989), Torrell *et al.* (1991), and McCluskey and Rausser (1999).

8 See Graetz (1986), Gutman *et al.* (1999), and Rehman *et al.* (1999).

model of a rangeland in which time restrictions are used to manage the rangeland. This model accounts for the ecological *and* the economic aspects of the range management problem. Second, we construct two managerial objectives that are ecologically and economically meaningful. These two managerial objectives incorporate in them specific probabilities that are derived from the dynamic and the stochastic properties of the rangeland. These probabilities can be given distinct ecological interpretations. An implication of viewing the range management problem in this way is that unlike most of the previous literature on this subject, our managerial objectives are explicitly ecological-economic in nature. Finally, using these two objectives, we discuss an approach to range management in which the manager has two interrelated goals. This manager maximizes the profits from range operations and (s)he also takes steps to move the rangeland away from the least desirable state of existence.

To the best of our knowledge, this is the *first* essay to provide an integrated approach to range management in a way that accounts for the ecological and the economic aspects of the underlying problem. We stress that the specific purpose of our chapter is to provide a *theoretical* perspective on the role of time in range management. We provide citations to the practical range management literature and we also mention the nexuses between our chapter and practical range management. Nevertheless, the reader should note that our objective in this chapter is *not* to conduct an investigation into the practical aspects of time based range management regimes.

Previous studies of resource management that are related to this chapter are the ones by Perrings and Walker (1995) and by Batabyal and Beladi (2002b). Like this chapter, Perrings and Walker (1995) provide an ecological-economic analysis of the range management problem. However, there are two key differences between this chapter and the Perrings and Walker (1995) paper. First, the decision variable in Perrings and Walker (1995) is the level of offtake and in our chapter it is the time restriction, i.e., the length of time during which grazing is terminated on the rangeland. Second, although Perrings and Walker (1995) are concerned about the resilience[9] of rangelands, they do not explicitly account for this concept in their optimization problems. In contrast, we do. Batabyal and Beladi (2002b) also provide an ecological-economic analysis of time restrictions in natural resource management. However, the specific methods of analysis and the goals of their paper and our chapter are very different. In particular, unlike the goals of this chapter, Batabyal and Beladi (2002b) are primarily interested in determining the likelihood of resource collapse when a resource is managed with time restrictions.

The rest of this chapter is organized as follows: Section 2 presents a semi-Markov model of a rangeland and constructs two objectives for the manger of our rangeland. Section 3 uses these objectives and discusses two optimization problems that a range manager might solve. Section 4 concludes and offers suggestions for future empirical and theoretical research on range management over time and under uncertainty.

2. Time Restrictions in a Dynamic and Stochastic Rangeland

2.1. Preliminaries

Recently, Perrings (1998) has suggested that researchers use a Markovian approach to study jointly determined ecological-economic systems. Further, a Markovian approach nicely captures the essential elements of the "state-and-transition" model of range ecology.[10] This chapter is the first to

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[9] Resilience refers to "the amount of disturbance that can be sustained [by a rangeland] before a change in system control or structure occurs." (Holling *et al.*, 1995, p. 50).

[10] For more on the "state-and-transition" model and the policy implications of this model see Westoby *et al.* (1989) and Batabyal and Godfrey (2002).

use the theory of semi-Markov processes[11] to model a rangeland. Consider a stochastic process with states $0,1,2,3,...,$ that is now in state i, $i \geq 0$, and that has the following two properties: First, the probability that it will next enter state j, $j \geq 0$, is given by the transition probability P_{ij}. Second, given that the next state to be entered is j, the time until the transition from state i to state j is a random variable with a general distribution function $F_{ij}(\cdot)$ where $F_{ij}^{c}(\cdot)=1-F_{ij}(\cdot)$. Now let $y(t)$ denote the state of the process at time t. Then $\{y(t):t \geq 0\}$ is a semi-Markov process.

In other words, a semi-Markov process is a Markov chain with one significant difference. Whereas a Markov chain spends one unit of time in a state before making a transition to some other state, a semi-Markov process stays in a particular state for a random amount of time before making a transition to some other state. Let K_i denote the distribution function of the time that $\{y(t):t \geq 0\}$ spends in state i before making a transition to some state and let β_i denote the expectation of this time in state i. Finally, let T_{ii} be the time between successive transitions into state i and let β_{ii} be the expectation of T_{ii}. That is, $\beta_{ii}=E[T_{ii}]$. We are now in a position to discuss the attributes of the rangeland that is the subject of this chapter.

2.2. The Dynamic and Stochastic Rangeland

Consider a dynamic and stochastic rangeland that is privately or publically held and whose *condition* can be in any one of three possible states.[12] In the language of range science, at a specific

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Lucid accounts of semi-Markov processes can be found in Medhi (1994, pp. 313-339) and in Ross (1996, pp. 213-218; 2000, pp. 395-397). Our discussion of semi-Markov processes and this section’s model are based in part on Ross (1996, pp. 213-218; 2000, pp. 395-397). We stress that our semi-Markov model is considerably more general than either a discrete-time Markov chain model or a continuous-time Markov chain model of a rangeland.

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As noted in Holechek *et al*. (2001, p. 184), range "condition refers to the state of health of the range."

point in time, this rangeland can exist in any one of three possible *condition classes*.[13] Further, the kind of rangeland we have in mind constitutes—in the words of Savory and Butterfield (1999, pp. 30-34)—a brittle environment.[14]

State 1 is the healthiest state of the rangeland. This means that in this state total forage is plentiful, the quality of this forage is high, and hence the rangeland is open for grazing. State 2 is an intermediate state. In this state, forage quality and quantity are both lower than in state 1 but the rangeland is not endangered in either an ecological or an economic sense. Consequently, the rangeland is still open for grazing. However, the manager now monitors the condition of the rangeland more carefully than in state 1. State 3 is the state in which the rangeland is endangered or least healthy. In this state, forage quality and quantity are low and the rangeland is severely degraded. Consequently, if the manager determines that the rangeland is in state 3, then no further grazing is permitted. In other words, a time restriction is now in place. The reader will note that we have envisioned the condition or health of a range in terms of the quality and the quantity of the total forage available for consumption. However, it is also possible to think of the condition of a range in terms of the population and the diversity of forage plants.

Let us now formalize the above remarks. As a result of ongoing grazing,

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Range managers frequently use the term "condition class" to refer to the state of a rangeland. See Stoddart *et al*. (1975, pp. 187-194) and Graetz (1986) for additional details. The justification for limiting the number of states to three is twofold. First, from a management perspective, rangelands are often conceptualized as existing in one of three possible states. As indicated in Box (1978, pp. 19-20), these states are "Excellent or Good," "Fair," and "Poor or Bad." Second, this three state model is simple and it captures the essential features of a dynamic and stochastic rangeland. Consequently, to keep the underlying management issues transparent, we have decided to analyze this three state model. For a practical application of this condition class classification scheme to prairie ranges in the central Great Plain of the United States, see Parker (1969).

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An example of such an environment would be either the sagebrush grassland or the salt desert shrubland of the American west. See Holechek *et al*. (2001, pp. 95-100) for more details.

ecological/environmental factors (droughts, lack of plant nutrients, unusually low soil moisture), and human induced factors (fires), our rangeland stays in state 1 for a mean length of time β_1 and then makes a transition either to state 2 with transition probability P_{12}, or to state 3 with transition probability P_{13}. When the rangeland is in state 2, once again because of the previously mentioned reasons, this rangeland will stay in state 2 for a mean length of time β_2 and then move to state 3 with transition probability P_{23}. When in state 3, grazing on this rangeland is terminated. As a result of the termination of grazing, the rangeland vegetation gradually recovers. It is important to note that the rate of recovery depends in part on the *extent* of rangeland degradation in state 3. What this means for our purpose is that the length of the recovery period—rest period in the words of Savory and Butterfield (1998, pp. 195-215)—or the length of time during which grazing is not permitted (the time restriction) is itself a *random* variable. Denote the mean length of the time restriction by β_3.[15]

The imposition of this time restriction does not guarantee that the rangeland will get back to the most desirable state 1. Rare events[16] may interact with the time restriction in a way that results in the rangeland recovering only to the intermediate state 2. To account for these features of the problem, we suppose that as a result of the time restriction, the rangeland returns either to state 1 with transition probability P_{31}, or to state 2 with transition probability P_{32}. Our task now is to use these dynamic and stochastic attributes of this rangeland and construct two objectives that our manager might optimize. However, before we do this, it is necessary to first say a few words about the applicability of this chapter's methodology to the determination of the fallow period in slash-and-

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15 In one practical time based range management regime in New Mexico, the grazing period was 5 days long and the recovery/rest period appears to have been about 28 days long. For more on this see Fowler and Gray (1986) and Holechek *et al.* (2001, pp. 269-271).

16 See Perrings and Walker (1995, pp. 192-195).

burn agriculture.

Slash-and-burn agriculture (also called swidden agriculture and shifting cultivation) is a common agricultural system in many developing countries.[17] In this system, forest or brush land is cleared with the slash-and-burn method—this releases nutrients held in plant tissues—and the soil is prepared with a dibble stick or a hoe. There is typically little use of irrigation systems or fertilizers and human labor is the single most important factor of production. The cleared land is generally multi-cropped and the cropping period is short. This cropping period is followed by a fallow period. As noted in Gleave (1996), Hofstad (1997), and Coomes *et al.* (2000), the length of the fallow period is an important choice variable in slash-and-burn agriculture. In particular, for slash-and-burn agriculture to be viable over any reasonable time horizon, the length of the fallow period must be selected optimally. Now, in the context of our chapter's semi-Markov model, if we think of state 3 as the fallow state and β_3 as the mean length of the fallow period, then it is possible to use methods similar to those employed in this chapter to choose the length of the fallow period to optimize, for instance, a farmer's profits from slash-and-burn agriculture. We now return to our range management problem.

2.3. Two Managerial Objectives

2.3.1. The First Objective: Asymptotic Resilience Weighted Profit Function

To derive the first managerial criterion, it will be necessary to compute the steady state probabilities for our three state rangeland. Formally, we are interested in computing $P_i = \lim_{t \to \infty} Prob\{y(t) = i / y(0) = j\}$ for any state j and for states $i = 1,2,3$. In words, given that our

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For more on slash-and-burn agriculture in developing countries, see Swinkels *et al.* (1997), Ekeleme *et al.* (2000), Li *et al.* (2000), Udaeyo *et al.* (2001), and the citations therein.

rangeland is in state j at time $t=0$, we want to compute the limiting probability, as time approaches infinity, that the rangeland will be in state i. To perform this computation, let us denote the limiting probabilities of the embedded Markov chain of our rangeland[18] by π_i, $i=1,2,3$. Now it is well known—see equation 7.23 in Ross (2000, p. 396)—that these limiting probabilities satisfy

$$\pi_j=\sum_{i=1}^{i=3} \pi_i P_{ij},\ \sum_{j=1}^{j=3} \pi_j=1. \tag{1}$$

Consequently, using the transition probabilities of the rangeland and equation (1), we can calculate the required limiting probabilities. These are

$$\pi_1=\frac{P_{31}}{1+P_{31}+P_{12}P_{31}+P_{32}},\ \pi_2=\frac{P_{12}P_{31}+P_{32}}{1+P_{31}+P_{12}P_{31}+P_{32}},\ \pi_3=\frac{1}{1+P_{31}+P_{12}P_{31}+P_{32}}. \tag{2}$$

To determine the steady state probabilities (the $P_i^{/}s$) of the rangeland, we now use equation 7.24 in Ross (2000, p. 396). This equation tells us that the $P_i^{/}s$ satisfy

$$P_i=\frac{\pi_i\beta_i}{\sum_{j=1}^{j=3} \pi_j\beta_j}. \tag{3}$$

Equations (2) and (3) together give us the steady state probabilities that we are after. We get

18 For additional details on the embedded Markov chain of a semi-Markov process, see Medhi (1994) and Ross (1996; 2000).

$$P_1 = \frac{P_{31}\beta_1}{P_{31}\beta_1 + (P_{12}P_{31} + P_{32})\beta_2 + \beta_3}, \tag{4}$$

and

$$P_2 = \frac{(P_{12}P_{31} + P_{32})\beta_2}{P_{31}\beta_1 + (P_{12}P_{31} + P_{32})\beta_2 + \beta_3},\ P_3 = \frac{\beta_3}{P_{31}\beta_1 + (P_{12}P_{31} + P_{32})\beta_2 + \beta_3}. \tag{5}$$

Equations (4) and (5) show us exactly how these three steady state probabilities depend on the time restriction β_3. Note that this time restriction is applied *only* if the manager determines that our rangeland is in state 3. Therefore, β_3 does not have any direct effect on either the probability of making a transition from state 1 to 3, P_{13}, or on the probability of making a transition from state 2 to 3, P_{23}. The purpose of β_3 is to affect the probability of making a transition to either state 1 or 2 *from state 3*, i.e., the transition probabilities P_{31} and P_{32}.[19]

In the context of this chapter's ecological-economic approach to the range management problem, these steady state probabilities have a distinct ecological meaning. As discussed in Krebs (1985, p. 587), Batabyal (1998a, 1998b, 1999, 2000), Perrings (1998), and Batabyal and Beladi (1999), these probabilities measure the asymptotic *resilience* of the rangeland in each of the three states. As indicated in footnote 10, resilience is an ecological stability property and it refers to "the amount of disturbance that can be sustained [by a rangeland] before a change in system control or structure occurs." (Holling *et al.*, 1995, p. 50). This means that we can think of the resilience of a rangeland as a long run measure of its well-being. Now, if we rank the three states from this well-

[19] For more on this, see the discussion in the second paragraph after equation (9) and inspect the objective function described in equations (10) and (13).

being perspective, then it should be clear that our rangeland's well-being is highest in state 1 because forage quality and quantity are plentiful in this state and the rangeland vegetation is not degraded. From a well-being perspective, state 2 is a middle-of-the-road state because forage quality and quantity are at an intermediate level. Finally, the rangeland is least well off in state 3 because in this state the rangeland is endangered. In the words of Perrings (1998), state 1 is a "desirable" state and state 3 is an "undesirable" state.

Recall that the range manager terminates grazing on the rangeland if and only if the rangeland is determined to be in state 3. Further, the mean length of this time restriction is β_3. Now, range operations result in revenues and in costs to our manager. To this end, let us denote the revenue and the cost functions (on which more later) in state i, i=1,2,3, by $R_i(\beta_i,\beta_3,w_i)$ and $C_i(\beta_i,\beta_3,a_i)$ respectively. In other words, the revenue from range operations in state i depends on the mean time spent in state i, β_i, the mean length of the time restriction β_3, and the total animal weight gain in state i, w_i. Similarly, the cost in the *ith* state is a function of the mean time spent in state i, β_i, the mean length of the time restriction β_3, and the various activities—such as range condition monitoring—associated with successful range management. We proxy these activities in state i by the variable a_i. We are now in a position to state our range manager's objective function. This objective function is the expected profit from range operations. Mathematically, we have[20]

$$Objective\ \ Function\ \ (i) = \sum_{i=1}^{i=3} P_i[R_i(\beta_i,\beta_3,w_i) - C_i(\beta_i,\beta_3,a_i)], \qquad (6)$$

20 It is understood that in state 3, β_3 enters the revenue and the cost functions only once.

where the $P_i^{/}s$ are given by equations (4) and (5).

Note that the steady state probabilities $P_i^{/}s$ in equation (6) denote both the long run proportion of time that our rangeland is in each of the three possible states and the asymptotic resilience of our rangeland in each of these three states. Consequently, these probability weights can be thought of as ecological correction factors to an economic objective function. This is the manner in which the ecology of the rangeland enters our manager's objective function.

In brittle environments of the sort that we are analyzing in this chapter, it is very important to choose the time restriction or recovery period carefully. It is clear that if the time restriction is too short, then our rangeland will not have had enough time to recover to either state 1 or 2 from state 3. However, this does *not* mean that the manager should err on the side of caution and, *ceteris paribus*, make the time restriction long. As Savory and Butterfield (1999, pp. 206-209) have pointed out, a recovery period that is much longer than the amount of time it takes for damaged plants to rebuild their root system is likely to be detrimental to the health of a brittle rangeland.

Moving to the economic side of the range management problem, we have already noted that range operations give rise to revenues and to costs.[21] To comprehend this clearly, first consider the revenue aspect. A well managed rangeland will be able to provide the manager with a flow of revenues in the different states. In state i, these revenues depend on β_i, β_3, and on the animal weight gain w_i. On the cost side, it is necessary to monitor the condition of the rangeland on an ongoing basis, and personnel involved in the various tasks associated with management have to be paid. We proxy these activities in state i with the variable a_i. Consequently, in deciding the length of the time

[21] For more on this see Fowler and Gray (1986), and Holechek *et al.* (2001, chapters 8 and 9).

restriction, in addition to the ecology of the rangeland, our manager must also pay attention to both the revenues and the costs from the time restriction. As such, the objective that our manager focuses on is the profit from range operations. When this profit is weighted by the steady state probabilities that denote the resilience of our rangeland, we get expected profit or asymptotic resilience weighted profit—shown in equation (6)—as our managerial objective function. This completes our discussion of the first managerial objective function.

2.3.2. The Second Objective: Transient Resilience in the Conditional Profit Function

The second managerial objective also involves profit maximization, but now the focus of the manager is a little different. As in section 2.3.1, once again we shall take a long run view of the rangeland. Specifically, suppose that at time t the rangeland is in the undesirable state 3. By choosing the time restriction β_3, the manager can affect not only the profits from range operations in the different states but also the state into which the rangeland will next make a transition. Ideally, the manager would like this next state to be the healthiest state, i.e., state 1. To this end, if we let $D(t)$ be the state entered at the first transition after time t, then we can determine the long run conditional probability that the next state visited after t is 1, given that at t the rangeland is in state 3 and that the mean length of the manager's time restriction is β_3. In other words, ideally, we would like to compute $\lim_{t\to\infty} Prob\{D(t)=1/y(t)=3\}$ and then use this probability to construct our manager's objective function. Note that unlike the steady state probabilities that we computed in the previous sub-section, that probability that we now seek is a steady state *conditional* probability.

We are now in a position to compute this probability. Elementary probability theory tells us that

$$\lim_{t\to\infty} Prob\{D(t)=1/y(t)=3\} = \lim_{t\to\infty} \frac{Prob\{D(t)=1, y(t)=3\}}{Prob\{y(t)=3\}}. \tag{7}$$

The joint probability in the numerator of the right-hand-side (RHS) of this equation can be simplified with the aid of Theorem 4.8.4 in Ross (1996, p. 217). The probability in the denominator of the RHS of equation (7) is simply P_3, the steady state probability (see equation (5)) of finding the rangeland in state 3. With these simplifications, we get

$$\lim_{t\to\infty} Prob\{D(t)=1/y(t)=3\} = P_{31} \bullet \frac{\int_0^\infty F_{31}^c(w)dw}{P_3 \beta_{33}}. \tag{8}$$

Proposition 4.8.1 in Ross (1996, p. 214) can be used to further simplify the denominator on the RHS of equation (8). This gives

$$\lim_{t\to\infty} Prob\{D(t)=1/y(t)=3\} = P_{31} \bullet \frac{\int_0^\infty F_{31}^c(w)dw}{\beta_3}. \tag{9}$$

The RHS of equation (9) is the product of two terms. The first term is the probability of making a transition from state 3 to 1. The second term is the ratio of the integral of the tail distribution of the amount of time the rangeland spends in state 3 before making a transition to state 1 to the mean length of the manager’s time restriction in state 3. Following Perrings (1998), we are now in a position to give an ecological interpretation to this first term. This term is the transient or the short run resilience of the rangeland in the least desirable state 3.

Let us now use the steady state conditional probability in equation (9) to construct our manager’s objective function. As in the previous sub-section, our range manager’s basic goal is to choose the mean length of the time restriction β_3 to maximize the profits from range operations. However, this time we shall focus on an alternate version of this profit maximization problem. Instead of maximizing the expected or the asymptotic resilience weighted profit from range operations, our manager now solves a *conditional* profit maximization problem in which the profits obtained in state 1 are conditional on the rangeland moving from state 3 to 1. In other words, using the notation of section 2.3.1, our manager is interested in $[R_1(\beta_1,\beta_3,w_1)-C_1(\beta_1,\beta_3,a_1)]$, the profits from range operations in state 1. However, state 1 arises only if the manager is able to choose the time restriction β_3 to move the rangeland from state 3 to 1. Given that the rangeland is currently in state 3, the conditional probability of moving to state 1 is given by equation (9). Consequently, our range manager's objective function now is a conditional profit function and this function is obtained by multiplying $[R_1(\beta_1,\beta_3,w_1)-C_1(\beta_1,\beta_3,a_1)]$ by the probability in equation (9). Mathematically, we have

$$\textit{Objective Function (ii)}=\lim_{t\to\infty}Prob\{D(t)=1/y(t)=3\}[R_1(\beta_1,\beta_3,w_1)-C_1(\beta_1,\beta_3,a_1)]. \quad (10)$$

In equation (10), β_1, β_3, w_1, and a_1 are as in the previous sub-section. However, note that because P_{31}, the transient resilience of our rangeland in state 3 is an argument of the stationary conditional probability in equation (9), the range manager's conditional profit function is itself a function of the rangeland's transient resilience in state 3. This is the way in which the ecology of the rangeland enters our manager's objective function.

The economic side of the management problem is a little different from what we had in the previous sub-section. The manager's objective function now is a profit function that is conditional on the rangeland moving from state 3 to 1. In determining the length of the time restriction, in addition to the ecology of the rangeland, our manager will now pay attention to the state 1 revenues and costs that arise probabilistically from the optimal choice of the time restriction. This completes our discussion of the second managerial objective and the associated managerial optimization problem. We now analyze these optimization problems and then draw inferences for range management.

3. Optimal Range Management With Ecological-Economic Criteria[22]

3.1. Maximizing the Asymptotic Resilience Weighted Profit Function

Recall from the discussion in section 2.3.1 that the first problem faced by our manager involves the maximization of an asymptotic resilience weighted profit function subject to a non-negative time restriction. Formally, our manager solves (see equation (6))

$$\max_{\{\beta_3\}} \sum_{i=1}^{i=3} P_i[R_i(\beta_i,\beta_3,w_i) - C_i(\beta_i,\beta_3,a_i)], \qquad (11)$$

subject to $\beta_3 \geq 0$.

Now, without loss of generality, suppose that the solution to problem (11) yields an interior maximum. Then, omitting the complementary slackness condition, the Kuhn-Tucker condition for a maximum is

$$K[P_{31}\beta_1\frac{\partial R_1}{\partial\beta_3} + (P_{12}P_{31}+P_{32})\beta_2\frac{\partial R_2}{\partial\beta_3} + \beta_3\frac{\partial R_3}{\partial\beta_3} + R_3] - P_{31}\beta_1 R_1 - (P_{12}P_{31}+P_{32})\beta_2 R_2 - \beta_3 R_3 =$$

$$K[P_{31}\beta_1\frac{\partial C_1}{\partial\beta_3} + (P_{12}P_{31}+P_{32})\beta_2\frac{\partial C_2}{\partial\beta_3} + \beta_3\frac{\partial C_3}{\partial\beta_3} + C_3] - P_{31}\beta_1 C_1 - (P_{12}P_{31}+P_{32})\beta_2 C_2 - \beta_3 C_3, \qquad (12)$$

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Our focus in this chapter is on the role of time in range management. This is why we are focusing exclusively on the optimal choice of β_3. This does not mean that the other arguments of the profit function are irrelevant.

where $K = P_{31}\beta_1 + (P_{12}P_{31} + P_{32})\beta_2 + \beta_3$.

The optimal time restriction, say β_3^*, solves equation (12). In words, this equation tells us that in choosing the time restriction optimally, the manager will balance ecological and economic considerations. Specifically, β_3^* will be chosen so that the marginal revenue from the time restriction (the LHS) equals its marginal cost (the RHS).

If the recovery period is chosen in this way, then we can be fairly sure that the rangeland will be healthy in the long run. From an ecological perspective, this means that the resilience of the rangeland in the relatively desirable states (1 and 2) will be high and its resilience in the undesirable state 3 will be low. In economic terms, this means that operations on this rangeland will provide our manager with a stream of profits in the long run.

3.2. Maximizing the Conditional Profit Function With Transient Resilience

Recall from section 2.3.2 that in this version of the management problem, the manager's objective is to choose the time restriction so that the conditional profit function in equation (10) is maximized. Formally (see equations (9) and (10)), our manager now solves

$$\max_{\{\beta_3\}} P_{31} \bullet \frac{\int_0^\infty F_{31}^c(w)dw}{\beta_3}[R_1(\beta_1,\beta_3,w_1) - C_1(\beta_1,\beta_3,a_1)], \qquad (13)$$

subject to $\beta_3 \geq 0$.

As stated, this maximization problem is unwieldy. Consequently, to illustrate our approach, we shall make a distributional assumption about the amount of time that the rangeland spends in state 3 before making a transition to state 1. Specifically, we suppose that this time is exponentially distributed. Then, integrating the tail distribution function for an exponentially distributed random variable—see Jeffrey (1995, p. 248)—and then evaluating this integral between the upper and the lower limits, we get

$$\int_0^\infty F_{31}^c(w)dw = \frac{1}{\delta}, \tag{14}$$

where $\delta > 0$ is the parameter of the exponential distribution function. Using equation (14), our manager's maximization problem becomes

$$\max_{\{\beta_3\}} \frac{P_{31}}{\delta\beta_3}[R_1(\beta_1,\beta_3,w_1) - C_1(\beta_1,\beta_3,a_1)], \tag{15}$$

subject to $\beta_3 \geq 0$. Now, as in the previous sub-section, suppose that the solution to problem (15) yields an interior maximum. Then, omitting the complementary slackness condition, the Kuhn-Tucker condition for a maximum is

$$\beta_3 \frac{\partial R_1}{\partial \beta_3} - R_1 = \beta_3 \frac{\partial C_1}{\partial \beta_3} - C_1. \tag{16}$$

The optimal time restriction, β_3^*, solves equation (16). This equation can be thought of as an "ecological-economic" optimality condition. In words, equation (16) tells us that when the manager's goal is to maximize the profits from range operations in state 1 after the rangeland has moved to this state from state 3, (s)he will choose the time restriction so that the long run conditional marginal revenue from the time restriction in state 1 (the LHS) is equal to the long run conditional marginal cost in this state (the RHS).

If β_3^* is chosen in this way, then one can be fairly sure that our rangeland will be sustainable in the long run. It is important to stress that in the context of our chapter, sustainability has a dual meaning. From an ecological standpoint, sustainable means that in the long run, the rangeland will not be resilient in the undesirable state 3. From an economic standpoint, sustainable means that the rangeland will provide our manager with a stream of profits in the long run. We now briefly discuss the salience and the policy implications of the research contained in this chapter.

3.3. Salience and Policy Implications of this Research

Holechek *et al.* (2001, p. 271, emphasis added) have noted that "a lack of *long-term* research [has prevented researchers from] drawing very many definite conclusions about the effectiveness of various [time-controlled] grazing strategies." In this chapter, we have provided a theoretical perspective on time-controlled grazing. Four specific policy conclusions follow from this chapter's research. First, unlike most economics papers on this subject, our chapter shows that successful range management involves paying attention to both the ecology and the economics of the rangeland under consideration. Second, we have shown that by maximizing the *long run* profit functions of this chapter, a range manager will also be enhancing the resilience of the desirable states (states 1 and 2) and lowering the resilience of the undesirable state 3. Third, this chapter has shown how a range manager might set the time restriction optimally in an ecological-economic context. Finally, from a practical perspective, this chapter sheds light on the probabilities that will need to be estimated in order to set up the objective functions described in equations (6) and (10). In addition to this, the maximization exercises of sections 3.1 and 3.2 provide the manager with two different ways of setting the time restriction optimally.

4. Conclusions

We addressed three issues in this chapter that, to the best of our knowledge, have not been addressed previously in the range management literature. First, in section 2, we used the theory of semi-Markov processes to provide an ecological-economic model of a rangeland that is managed with time restrictions. Next, we used the dynamic and the stochastic properties of this rangeland to construct two managerial objective functions that are meaningful from an ecological and an economic standpoint. We stress that because these two objectives are ecological-economic in nature, our modeling of the range management problem is quite different from previous approaches to this problem in the economics literature. Finally, in section 3, we used these two objectives to analyze two range management problems from an ecological-economic perspective. In this perspective, the focus of the manager is on using the time restriction to (i) maximize the profits from range operations and (ii) move the rangeland away from the least desirable state of existence.

The analysis contained in this chapter can be extended in a number of different directions. In what follows, we suggest three avenues for empirical and theoretical research on the subject of range management over time and under uncertainty. First, it would be useful to determine whether extant econometric techniques can be used to estimate the transition probabilities of the rangeland under study. Second, given a specific grazing system such as time-controlled grazing, knowledge of the amount of time a rangeland spends in a particular condition class or state would be helpful in setting up the objective functions discussed in this chapter. Finally, we modeled the rangeland as a three state semi-Markov process. Although this is consistent with the "condition class" view of rangelands that is frequently employed by range scientists, it would still be useful to generalize the theoretical analysis of this chapter to an arbitrary but finite number of states. Studies of range management that incorporate these aspects of the problem into the analysis will provide additional insights into the management of rangelands whose behavior is marked by a considerable amount of uncertainty.

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