2001 AAEA Annual Meeting, Chicago, Illinois

On the Choice Between the Stocking Rate and Time in Range Management[1]

by

AMITRAJEET A. BATABYAL,[2]

BASUDEB BISWAS,[3]

and

E. BRUCE GODFREY[4]

1

We thank Michael Rauscher and two anonymous referees for their helpful comments on a previous version of this paper. Batabyal acknowledges financial support from the Utah Agricultural Experiment Station, Utah State University, Logan, UT 84322-4810, by way of project UTA 024 and from the Gosnell endowment at RIT. The usual disclaimer applies.

2

Department of Economics, Rochester Institute of Technology, 92 Lomb Memorial Drive, Rochester, NY 14623-5604, USA. Internet **aabgsh@rit.edu**

3

Department of Economics, Utah State University, 3530 Old Main Hill, Logan, UT 84322-3530, USA. Internet **biswas@b202.usu.edu**

4

Department of Economics, Utah State University, 3530 Old Main Hill, Logan, UT 84322-3530, USA. Internet **bruceg@b202.usu.edu**

On the Choice Between the Stocking Rate and Time in Range Management

Abstract

A long standing question in range management concerns the relative importance of the *stocking rate* versus the length of *time* during which animals graze a particular rangeland. We address this question by analyzing the problem faced by a private rancher who wishes to minimize the long run expected net unit cost $(LRENC)$ from range operations by choosing either the stocking rate or the length of time during which his animals graze his rangeland. We construct a renewal-theoretic model and show that, in general, this rancher's $LRENC$ with an optimally chosen stocking rate is *lower* than his $LRENC$ with an optimally chosen grazing cycle length. From a management perspective, this means that correct stocking of the range is more important than the length of time during which animals graze the range. In addition, our research shows how to address questions concerning the desirability of temporal versus non-temporal controls in managing natural resources such as fisheries and hunting grounds.

Keywords: Long Run Expected Net Cost, Range Management, Stocking Rate, Time

JEL Classification: Q24, D81

1. Introduction

1.1. Preliminaries

All parts of the world that are not bare deserts, that are not cultivated, and that are not covered by bare soil, ice, or rock can be thought of as *rangelands*. This means that rangelands include most deserts, forests, and all natural grasslands. The key feature of a rangeland is that it consists of uncultivated land that can and typically does provide habitat for browsing and grazing animals. *Browsing* refers to the consumption of leaves and twigs from woody plants such as shrubs and trees by animals. In contrast, *grazing* refers to the consumption of standing forage such as grasses by animals.

Range management is "the manipulation of rangeland components to obtain the optimum combination of goods and services for society on a sustained basis" (Holechek *et al.*, 1998, p. 5). As noted by Stoddart *et al.* (1975, pp. 2-3) and by Holechek *et al.* (1998, p. 5), in contemporary times, the task of range management is based on five basic precepts. First, a rangeland is a renewable resource. Second, solar energy captured by the green plants of a rangeland can only be harvested by browsing and grazing animals. Third, the productivity of a rangeland is determined by climatic, soil, topographic, and use factors. Fourth, in comparison with cultivated lands, rangelands provide humans with food and fiber at very low energy costs. Finally, a variety of goods and services such as food, minerals, timber, and recreation are obtained from rangelands.

A range manager can manipulate the components of a rangeland in several ways. In other words, this manager can accomplish his managerial objectives[5] with a variety of choice variables. In this paper, we are interested in shedding light on a particular controversy in the range management literature. This controversy concerns two choice variables, namely, the stocking rate and the length of a grazing cycle. The *stocking rate* concept is used in more than one way by range managers. Consequently, it is important to be clear about the precise meaning of this concept. The meaning that we shall use in this paper tells us that the "stocking rate is typically expressed as animal units per section of land" (Holechek *et al.*, 1998, p. 190). The *length of a grazing cycle* is more straightforward and it is defined to be the length of time in a calender year during which animals graze a given rangeland.[6]

With these two definitions in place, we are now in a position to state the above mentioned controversy in the form of a simple question: Is the stocking rate more important or is time more important in range management? The objective of this paper is to answer this question. We now discuss this range management controversy in greater detail and then we comment on the way in which we plan to address the underlying issues.

1.2. The controversy

Although there are many aspects to the task of range management, today, range scientists agree that one important aspect concerns the determination of the appropriate stocking rate. Consider the position of two standard range management texts on the subject of the stocking rate. Stoddart *et al.* (1975, p. 262) tell us that correct livestock "numbers are important for the perpetuation of the

---

5

Examples include the maximization of (i) range livestock productivity and (ii) the economic returns from the rangeland.

6

In the rest of this paper, we shall use the terms "length of grazing cycle" and "time" interchangeably. The reader should note that both these terms refer to the length of time during which animals graze a given rangeland.

range, the well-being of the livestock, and the economic stability of the operator." Holechek *et al.* (1998, p. 221) go even further and state that proper "stocking is the most important part of successful range management."

However, not everyone agrees that the stocking rate is the most salient part of successful range management. In particular, Allan Savory (1983, 1988) and his adherents—see Goodloe (1969), Savory and Parsons (1980), and Savory and Butterfield (1998)—have forcefully argued that the stocking rate is *less* important than is commonly believed. Savory and Butterfield (1998, p. 41, emphasis in original) have pointed out that until "very recently no one truly explored the question of *when* animals are there as opposed to how many there are." The central point of Allan Savory and other like minded scholars is this: Overgrazing bears "little relationship to the number of animals but rather to the *time* plants [are] exposed to the animals" (Savory and Butterfield, 1998, p. 46, emphasis in original).[7]

This polarized state of affairs raises an important question. Is the stocking rate more important or is time, i.e., the length of the grazing cycle, more important in range management? We shall answer this question by analyzing the decision problem faced by an optimizing private rancher. Keeping with standard practice in economics, we suppose that this rancher wishes to maximize the long run expected profit—or equivalently, minimize the long run expected net unit cost (hereafter $LRENC$)—from his range operations. This rancher does so by choosing either the stocking rate or

---

[7] Allan Savory's views on grazing have been variously described as time-controlled grazing, as short-duration grazing, and as the Savory grazing method. For more on this and related issues, see Holechek *et al.* (1998, pp. 229-256). A related issue here concerns plant recovery times after different degrees of grazing. For more on this, see Hart *et al.* (1988), Hall *et al.* (1992), and McCreary and Tecklin (1993).

the length of time during which his animals graze his rangeland.[8] Note that this *long run* focus means that our rancher cares about the expected net cost from his range operations *and* about the well being of his rangeland. Moreover, this focus also implies that the rancher will not stock his rangeland at a rate that the rangeland is unable to support. Our analysis shows that, in general, this rancher's $LRENC$ with an optimally chosen stocking rate is *lower* than his $LRENC$ with an optimally chosen grazing cycle length.

To intuitively see why this result holds, note the following two things. First, because the two choice variables under consideration here are different—the stocking rate is a *quantity* control variable and the grazing cycle length is a *temporal* control variable—the rancher's objective functions with these two choice variables are dissimilar. Second, in the presence of uncertainty, the two choice variables under consideration affect the rancher's objective function in different ways. The net impact of these two things is that our rancher's minimized $LRENC$ with an optimally chosen grazing cycle length is higher than his minimized $LRENC$ with an optimally chosen stocking rate by a specific additive factor. This additive factor is $c/2$, where c can be thought of as the instantaneous net cost of grazing an animal.

At the outset, it is important to be clear about the conclusions that can be drawn from our analysis. Our analysis tells us that when confronted with a choice *between* the stocking rate and the grazing cycle length, a rational rancher would choose the stocking rate. We are *not* saying that the grazing cycle length is irrelevant for management purposes. Further, it is our conjecture that just as part-price and part-quantity control instruments dominate pure price and pure quantity control

8 To keep the mathematics straightforward, in the rest of this paper, we shall not focus on the profit criterion; instead, we shall focus on the *LRENC* criterion. However, the reader should note that maximizing profit is equivalent to minimizing net cost.

instruments (see Roberts and Spence (1976), Weitzman (1978), and Batabyal (1995)), a hybrid control instrument that is part-stocking rate and part-time is likely to be more useful for range management than the stocking rate or the grazing cycle length alone. Having said this, we should note that the simultaneous use of the two control variables under consideration here is not mandatory. Just as it is not always necessary to use price and quantity control instruments simultaneously to regulate pollution, similarly, in this range management context, it is not imperative that a range manager use a temporal control (grazing cycle length) and a quantity control (stocking rate) concurrently.

Given the obvious importance of this stocking rate versus time question for practical range management, one would expect this question to have been studied thoroughly. Although there are many studies that have evaluated the impact of alternate stocking rates on animal performance and on forage production,[9] and some empirical studies of Allan Savory's time-controlled grazing,[10] these studies have not resolved this stocking rate versus time controversy. Moreover, on the theoretical side, the matter is even less settled. To the best of our knowledge, there are *no* previous theoretical studies of this question. This state of affairs has led Holechek *et al.* (1998, p. 254) to conclude that the long "term impacts of [time-controlled] grazing...[have yet] to be determined." As such, we now proceed to our analysis of the long run effects of the stocking rate versus time in range management.

The theoretical framework of this paper is adapted from Batabyal (1999) and the rest of this paper is organized as follows. Section 2 presents and analyzes a renewal-theoretic[11] model of the

---

9 See Holechek *et al.* (1998, pp. 248-256) and Holecheck *et al.* (1999).

10 See Graham *et al.* (1992), Hart *et al.* (1993), and Holechek *et al.* (1998, pp. 248-256).

11 For more on renewal theory, see Ross (1996, pp. 98-161; 1997, pp. 351-410) and Taylor and Karlin (1998, pp. 419-472).

decision problem faced by a private rancher who wishes to minimize his *LRENC* from range operations by choosing the stocking rate optimally. Section 3 analyzes a similar model; however, in this section, the rancher minimizes his *LRENC* from range operations by choosing the length of the grazing cycle optimally. Section 4 first compares the optimized value of the rancher's *LRENC* from sections 2 and 3 and thereby determines which choice variable—stocking rate or time—results in lower *LRENC*. Next, this section discusses the relationship between the analysis of this paper and other related natural resource management problems. Section 5 concludes and offers suggestions for future research.

2. Range Management with an Optimally Chosen Stocking Rate

Consider a private rancher who owns livestock animals (cows) and a fenced plot of rangeland. In the model of this and the next section, our private rancher conducts his range operations with reference to a particular grazing period in a calender year. For instance, this grazing period might be from May 2 to July 15, which would correspond to the grazing period for intensive-early stocking, or it might run from May 2 to October 3, which would correspond to the grazing period for normal season-long grazing (Holechek *et al.*, 1998, pp. 231-236). At the beginning of a grazing period, our rancher lets his animals into his fenced rangeland in accordance with an arrival process. In general, this arrival process could be any renewal process. However, in both the economics and the ecology literatures, the Poisson process has been frequently used to study natural resource phenomena.[12] Consequently, we suppose that this arrival process is the Poisson process with rate á.[13] This rancher

[12] See Uhler and Bradley (1970), Pielou (1977), Arrow and Chang (1980), Mangel (1985), and Batabyal and Beladi (2000a) for a more detailed corroboration of this claim.

[13] For more on the Poisson process, see Ross (1996, pp. 59-97; 1997, pp. 249-301) and Taylor and Karlin (1998, pp. 267-332). The rate of the (Poisson) arrival process might depend on the stock of animals. One way to model this would be to work with a

believes that the appropriate stocking rate for his rangeland corresponds to A animals. As such, once A animals have been allowed into the rangeland to graze, entry of additional animals is prohibited for the grazing period under consideration. Put differently, once A animals have been allowed in, this rancher's rangeland is closed to grazing in the current calender year grazing period.

As a result of his range operations, our rancher incurs costs and obtains benefits from two sources. The first, or direct, source of net cost (total cost less total benefit) stems from things like the deleterious effects of grazing on the plant species of the rangeland (a cost) and from the weight gain accruing to animals as a result of forage intake (a benefit). We capture this direct source of net cost by supposing that our rancher incurs net cost at the rate of $\$ac$ per unit time, where a refers to the number of animals grazing at that time and c can be thought of as the instantaneous net cost per animal. The second, or indirect, source of net costs arises from things like the need to feed animals that have not been allowed in to the rangeland (a cost) and from stocking the rangeland at the correct rate (a benefit). This benefit arises because correct stocking means that the rangeland's grazing capacity will not be exceeded. In turn, this means that this rangeland will be able to provide the rancher's animals with a flow of forage in the long run. In every calender year grazing period, we suppose that our rancher incurs a net cost of $\$C,$ when he closes his rangeland to additional animals.

Now, if we say that a grazing cycle[14] for the calender year is completed whenever the rancher

---

nonhomogeneous Poisson process for which the arrival rate at time t is a function of t. That is, the arrival rate (also called the intensity function) is á(t), $t \geq 0$. Now if this intensity function is bounded, i.e., if á(t)≤â, ∀$t \geq 0$, then we can think of the nonhomogeneous Poisson process as being a random sample from the homogeneous Poisson process with rate â. Specifically, we could work with this new Poisson process and the analysis would go through as indicated in the paper. Finally, note that the range management problem being analyzed in this paper is directly concerned with the number of animals and the length of time during which animals are *on the rancher's rangeland*. The question of how the animals leave the rangeland is not of interest. Formally, the problem being analyzed is *not* a queuing problem. As such, it is not necessary to formally model the departure process.

[14] The use of the word "cycle" is appropriate because the events that we are studying here are cyclical in nature. First, with regard to the analysis in this section, a cycle is completed whenever the rangeland is closed to grazing by animals. Similarly, with respect to the analysis in section 3, a cycle is completed whenever T for that calender year expires. Second, this pattern of events is repeated

closes the rangeland to additional animals, then the description of events in the previous two paragraphs constitutes a renewal-reward process.[15] This fact is useful because we can now use a key property of renewal-reward processes, namely, the renewal-reward theorem to compute our rancher's $LRENC$ from his range operations. The reader should note that the rancher's objective function involves the minimization of an economic criterion, i.e., the long run expected net cost. The renewal-reward theorem tells us how to compute this economic criterion. Specifically, this theorem tells us that the rancher's $LRENC$ equals the expected net cost in a grazing cycle divided by the expected length of this grazing cycle. Formally, we have

$$LRENC = \frac{E[net\ cost\ per\ grazing\ cycle]}{E[length\ of\ grazing\ cycle]}, \quad (1)$$

where $E[\cdot]$ is the expectation operator.

Let us now compute the two expectations on the right hand side (hereafter RHS) of equation (1). In any given grazing cycle, let X_a denote the time between the arrival of the ath animal and the $(a+1)th$ animal into the rancher's rangeland. Then the numerator on the RHS of equation (1) is given by

$$E[net\ cost\ per\ grazing\ cycle] = C + E[1cX_1 + 2cX_2 + 3cX_3 + \ldots + (A-1)cX_{A-1}]. \quad (2)$$

Because the rancher's cows are brought into the rangeland in accordance with a Poisson process with rate $á$, the mean interarrival time is $1/á$. Mathematically, this means that $E[X_i] = 1/á$, $i = 1,\ldots,(A-1)$.

---

every calender year and we are examining the long run behavior of this cyclical pattern of events.

15 For more on renewal-reward processes and the renewal-reward theorem, see the references cited in footnote 11. Also, see the motivation for the rancher's objective function in section 1.2.

Using this result, the RHS of equation (2) can be simplified to

$$E[net\ \ cost\ \ per\ \ grazing\ \ cycle] = C + \frac{cA(A-1)}{2á}. \tag{3}$$

In order to compute the denominator on the RHS of equation (1), it suffices to note that the expected length of a grazing cycle is simply the expected time it takes for the A animals to begin grazing on the rancher's rangeland. Because the mean interarrival time for the cows is $1/á,$ we get

$$E[length\ \ of\ \ grazing\ \ cycle] = \frac{A}{á}. \tag{4}$$

Now combining the results from equations (3) and (4), we get an expression for the rancher's $LRENC.$ That expression is

$$LRENC = \frac{áC}{A} + \frac{c(A-1)}{2}. \tag{5}$$

Having computed the expression for our rancher's $LRENC,$ we are now in a position to state this rancher's $LRENC$ minimization problem. Specifically, this rancher chooses the stocking rate A to minimize the $LRENC$ from his range operations. Formally, our rancher solves

$$\min_{\{A\}}[\frac{áC}{A} + \frac{c(A-1)}{2}]. \tag{6}$$

Treating A as a continuous choice variable and using calculus, we see that the stocking rate that minimizes the rancher's $LRENC$ is given by[16]

$$A^{*} = \sqrt{\frac{2áC}{c}}. \tag{7}$$

In words, the optimal stocking rate equals the square root of the ratio of the product of twice the rate of the Poisson arrival process $(á)$ and the indirect net cost from closing the rangeland to additional animals (C) to the instantaneous net cost per animal (c). Inspecting equation (7) it is easy to verify two properties of the optimal stocking rate. First, as the indirect net cost per grazing cycle (C) goes up, the rancher finds it desirable to *raise* the optimal stocking rate. Second, if the instantaneous net cost per animal (c) increases, then it is in the interest of the rancher to *lower* the optimal stocking rate.

Let us now substitute the expression for the optimal stocking rate from equation (7) into the minimand in equation (6). This gives us an expression for the minimal $LRENC$ that our rancher will incur by choosing the stocking rate optimally. Denote this minimal $LRENC$ by $(LRENC)^{*}_{SR}$. Some algebra tells us that

$$(LRENC)^{*}_{SR} = \sqrt{2ácC} - \frac{c}{2}. \tag{8}$$

Inspecting equation (8), we see that the minimal $LRENC$ that our rancher will incur by choosing the stocking rate optimally equals the square root of the product of twice the rate of the

16 The second order condition is satisfied.

Poisson arrival process (á), the instantaneous net cost per animal (c), and the indirect net cost per grazing cycle (C), less one-half the instantaneous net cost per animal.

We now study the case in which the focus of our private rancher is not on the stocking rate *per se*, but on the *length* of the grazing cycle on his rangeland. After computing the optimal length of the grazing cycle, we shall compare equation (8) with the corresponding equation for this latter case in which the rancher's focus is on time.

3. Range Management with an Optimally Chosen Grazing Cycle Length

Instead of choosing the stocking rate optimally, our rancher now follows a different strategy. In particular, this rancher now chooses the length of the grazing cycle (T) to minimize the $LRENC$ from his range operations. In the context of the discussion in the first paragraph of section 2, this means that if the grazing period in a calender year happens to be 75 days long (May 2 to July 15), then our rancher chooses T with this 75 day grazing period in mind.[17] So, in this example, the optimal T would be some real number between 0 and 75. If the optimal T=0, then this means that the rancher rests his rangeland for the entire grazing period in that calender year. At the other end, if optimal T=75, then this means that the rancher's grazing cycle and the grazing period for that calender year coincide.

In this setting, our rancher chooses the length of the grazing cycle (time) to minimize the $LRENC$ from his range operations. Consequently, let us now compute the $LRENC$ that is incurred by the rancher when this rancher's focus is on time rather than on the stocking rate. As in the previous section, at the beginning of the grazing period, our rancher lets his animals into his rangeland

17

The reader should note that the length of the grazing period in a calender year and the choice of T will depend, *inter alia*, on the geographic location of the rangeland in question. Specifically, the recovery time and the capability of a range in a wet and humid region will be very different from the recovery time and capability of a range in an arid and /or semiarid region.

in accordance with a Poisson process with rate α. We suppose that this rancher lets his animals graze the rangeland for T units of time. In other words, when T units of time have elapsed, the rangeland is closed to grazing. This means that a grazing cycle is completed when T units of time have elapsed. As explained in the previous paragraph, the length of this grazing cycle will either be less than or equal to the length of the grazing period in a calender year.

We shall use the renewal-reward theorem (equation (1)) to compute our rancher's $LRENC$. The computation of $E[net\ cost\ per\ grazing\ cycle]$ will be facilitated by conditioning on $N(T)$, the total number of animals that are grazing the rancher's rangeland by time T. This yields

$$E[net\ cost\ per\ grazing\ cycle/N(T)] = C + \frac{cTN(T)}{2}. \tag{9}$$

Using the properties of the expectation operator and equation (9), we get

$$E[net\ cost\ per\ grazing\ cycle] = C + \frac{\alpha c T^2}{2}. \tag{10}$$

Now note that $E[length\ of\ grazing\ cycle] = T$. This result and equation (10) together tell us that our rancher's $LRENC$ is given by

$$LRENC = \frac{C}{T} + \frac{\alpha c T}{2}. \tag{11}$$

Having computed the expression for our rancher's $LRENC$, we are now in a position to state this rancher's $LRENC$ minimization problem. This rancher chooses the length of the grazing cycle (T)

to minimize the $LRENC$ from his range operations. Formally, our rancher solves[18]

$$\min_{\{T\}}[\frac{C}{T}+\frac{\acute{a}cT}{2}]. \tag{12}$$

Using calculus, we see that the grazing cycle length that minimizes the rancher's $LRENC$ is given by[19]

$$T^{*}=\sqrt{\frac{2C}{\acute{a}c}}. \tag{13}$$

In words, the optimal length of the grazing cycle equals the square root of the ratio of the product of twice the indirect net cost from closing the rangeland (C) to the product of the rate of the Poisson arrival process $(\acute{a})$ and the instantaneous net cost per animal (c). Inspecting equation (13) it is easy to verify two properties of the optimal length of the grazing cycle. First, as the indirect net cost per grazing cycle (C) goes up, the rancher finds it optimal to *lengthen* the grazing cycle. Second, if the instantaneous net cost per animal (c) increases, then it is optimal for the rancher to *shorten* the grazing cycle.

Let us now substitute the expression for the optimal length of the grazing cycle from equation (13) into the minimand in equation (12). This gives us an expression for the minimal $LRENC$ that our rancher will incur by choosing the grazing cycle length optimally. Denote this minimal $LRENC$ by $(LRENC)^{*}_{T}$.

[18] To keep this minimization problem simple, we have not imposed a constraint requiring T to be bounded below by zero and above by the length of the grazing period in a calender year. If the optimal T turns out to be larger than the length of the grazing period, then we simply set the optimal T equal to the length of the grazing period. For example, as discussed in the first paragraph of this section, if the length of the grazing period happens to be 75 days and the optimal T turns out to be 78 days, then we simply set this optimal T equal to 75 days.

[19] The second order condition is satisfied.

After some algebra, we get

$$(LRENC)_T^* = \sqrt{2 \acute{a} c C}. \tag{14}$$

Inspecting equation (14), we see that the minimal $LRENC$ that our rancher will incur by choosing the grazing cycle length optimally equals the square root of the product of twice the rate of the Poisson arrival process $(\acute{a})$, the instantaneous net cost per animal (c), and the indirect net cost per grazing cycle (C).

Recall that the objective of this paper is to answer the following question: Is the stocking rate more important or is time, i.e., the length of the grazing cycle, more important in range management? We now provide an answer to this question.

4. Stocking Rate versus Time in Range Management

Equation (8) gives us an expression for the $LRENC$ incurred by our rancher when he chooses the stocking rate optimally. Similarly, equation (14) gives us an expression for this rancher's $LRENC$ when he chooses the length of the grazing cycle (time) optimally. Comparing these two expressions, we see that

$$(LRENC)_{SR}^* = \sqrt{2 \acute{a} c C} - \frac{c}{2} < \sqrt{2 \acute{a} c C} = (LRENC)_T^*. \tag{15}$$

Equation (15) clearly tells us that the rancher's $LRENC$ with an optimally chosen stocking rate is *lower* than his $LRENC$ with an optimally chosen grazing cycle length. It is in this sense that the stocking rate is *more important* than time in range management. Put differently, if a rational rancher had to choose a single control variable from a control set consisting of the stocking rate and time, then this rancher would choose the stocking rate over time. We now discuss the relationship between the analysis of this paper and other related natural resource management problems.

4.1. Our analysis and other resource management problems

In addition to rangelands, a number of other natural resources are also managed with temporal and non-temporal choice variables. For instance, commercial and recreational hunters for most game are subject to seasonal (time) restrictions. Moreover, such hunters are generally required to hunt during daylight hours. Similarly, Batabyal and Beladi (2000b) have pointed out that most commercial fisheries are subject to season length (time) restrictions. Given this state of affairs, it would certainly be useful to know whether society is better off with such temporal restrictions or whether non-temporal choice variables—such as the number of animals hunted and the number of fishing boats used—result in higher welfare to society.

The theoretical framework of this paper can be used to answer these sorts of questions. Specifically, in the context of range management decisions, our analysis leads to three conclusions. First, *ceteris paribus*, correct stocking of the range is more important than the length of time during which animals graze the range. This conclusion supports the view that proper "stocking is the most important part of successful range management" (Holechek *et al.*, 1998, p. 221). Second, there are circumstances in which the use of a non-temporal choice variable like the stocking rate leads to lower costs for the rancher. As such, it would be useful to see if one can make a general theoretical argument against the use of temporal choice variables in range management. Finally, although we have come down on the side of the stocking rate, it is clear that because of biological factors such as the differential recovery rates of plants subject to grazing, there is a difference between grazing 10 animals for 100 days and grazing 100 animals for 10 days. In other words, the length of the grazing cycle is a relevant choice variable. This suggests that from a management perspective, stochastic but relevant biological factors are likely to be better accounted for by the use of control instruments that are part-stocking rate and part-time. We now discuss this issue in greater detail.

5. Conclusions

In this paper, we used a renewal-theoretic approach to analyze the decision problem faced by a private rancher who is interested in minimizing the *LRENC* from his range operations. On the basis of our analysis of two optimization problems for this rancher, we concluded that the stocking rate is more important than time in range management. To the best of our knowledge, this is the *first* theoretical answer to this stocking rate versus time question in range management.

The analysis of this paper can be extended in a number of directions. In what follows, we suggest two possible extensions. First, the discussion in the last paragraph of section 4.1 suggests that there might exist choice variables, intermediate between the stocking rate and time, that dominate these two control variables. With regard to this issue, consider the seminal work of Roberts and Spence (1976). Environmental economists now know that is possible to construct an "intermediate" control instrument that is part-price (fee or tax) and part-quantity (emissions permit scheme). Roberts and Spence (1976) showed that this intermediate control instrument can always be converted into a pure price or pure quantity control instrument. Consequently, in comparison with either a pure price or pure quantity control instrument, a regulator will do at least as well—and often much better—with this intermediate control instrument. A useful extension of this paper would be to determine whether this logic carries over to the subject of range management. In other words, the open question is to check whether it is possible to construct, in a dynamic and stochastic setting, a control instrument that is intermediate in the sense that it is part stocking rate and part time. If it is possible to do so, then it should be fairly straightforward to demonstrate that this intermediate control instrument dominates a pure stocking rate and a pure time control instrument.

Second, in section 2, we studied the decision problem faced by a private rancher who owns a single species of livestock animals (cows). As such, it would be useful to ascertain whether the results of this paper hold when this rancher's decision problem with the stocking rate as a choice variable is modified to account for situations in which the rancher owns more than one animal species. Studies of range management that incorporate these aspects of the problem into the analysis will provide additional insight into the roles that the stocking rate and time play in successful range management.

References

Arrow, K.J., and Chang, S.S.L. 1980. Optimal Pricing, Use, and Exploration of Uncertain Natural Resource Stocks, in P.T. Liu, (ed.), *Dynamic Optimization and Mathematical Economics*. Plenum Press, New York, NY, USA.

Batabyal, A.A. 1995. Leading Issues in Domestic Environmental Regulation: A Review Essay, *Ecological Economics*, 12, 23-39.

Batabyal, A.A. 1999. Aspects of the Optimal Management of Cyclical Ecological-Economic Systems, *Ecological Economics*, 30, 285-292.

Batabyal, A.A., and Beladi, H. 2000a. Aspects of the Theory of Financial Risk Management for Natural Disasters. Forthcoming, *Applied Mathematics Letters*.

Batabyal, A.A., and Beladi, H. 2000b. Time Restrictions in Natural Resource Management: A Dynamic and Stochastic Analysis, *Unpublished Manuscript*, Rochester Institute of Technology.

Goodloe, S. 1969. Short Duration Grazing in Rhodesia, *Journal of Range Management*, 22, 369-373.

Graham, K.T., Torell, L.A., and Allison, C.D. 1992. Costs and Benefits of Implementing Holistic Resource Management on New Mexico Ranches. *New Mexico Agricultural Experiment Station Bulletin 672*.

Hall, L.M., George, M.R., McCreary, D.D., and Adams, T.E. 1992. Effects of Cattle Grazing on Blue Oak Seedling Damage and Survival, *Journal of Range Management*, 45, 503-506.

Hart, R.H., Samuel, M.J., Test, P.S., and Smith, M.A. 1988. Cattle Vegetation and Economic Responses to Grazing Systems and Grazing Pressure, *Journal of Range Management*, 41, 282-286.

Hart, R.H., Clapp, S., and Test, P.S. 1993. Grazing Strategies, Stocking Rates and Frequency

Intensity of Grazing on Western Wheatgrass and Blue Grama, *Journal of Range Management*, 46, 122-127.

Holechek, J.L., Pieper, R.D., and Herbel, C.H. 1998. *Range Management*, 3rd edition. Prentice Hall, Upper Saddle River, NJ, USA.

Holechek, J.L., Thomas, M., Molinar, F., and Galt, D. 1999. Stocking Desert Rangelands: What We've Learned, *Rangelands*, 21, 8-12.

Mangel, M. 1985. *Decision and Control in Uncertain Resource Systems*. Academic Press, Orlando, FL, USA.

McCreary, D.D., and Tecklin, J. 1993. Tree Shells Accelerate Valley Oak Restoration on Grazed Rangelands (California), *Restoration and Management Notes*, 11, 152.

Pielou, E.C. 1977. *Mathematical Ecology*. Wiley, New York, NY, USA.

Roberts, M., and Spence, M. 1976. Effluent Charges and Licenses Under Uncertainty, *Journal of Public Economics*, 5, 193-208.

Ross, S.M. 1996. *Stochastic Processes*, 2nd edition. Wiley, New York, NY, USA.

Ross, S.M. 1997. *Introduction to Probability Models*, 6th edition. Academic Press, San Diego, CA, USA.

Savory, A. 1983. The Savory Grazing Method or Holistic Resource Management, *Rangelands*, 5, 155-159.

Savory, A. 1988. *Holistic Resource Management*. Island Press, Washington, DC, USA.

Savory, A., and Parsons, S.D. 1980. The Savory Grazing Method, *Rangelands*, 2, 234-237.

Savory, A., and Butterfield, J. 1999. *Holistic Management*, 2nd edition. Island Press, Washington, DC, USA.

Stoddart, L.A., Smith, A.D., and Box, T.W. 1975. *Range Management*, 3rd edition. McGraw Hill, New York, NY, USA.

Taylor, H.M., and Karlin, S. 1998. *An Introduction to Stochastic Modeling*, 3rd edition. Academic Press, San Diego, CA, USA.

Uhler, R.S., and Bradley, P.G. 1970. A Stochastic Model for Determining the Economic Prospects of Petroleum Exploration Over Large Regions, *Journal of the American Statistical Association*, 65, 623-630.

Weitzman, M.L. 1978. Optimal Rewards for Economic Regulation, *American Economic Review*, 68, 683-691.