Optimal Stocking of Rangeland for Livestock Production within a Dynamic Framework

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A dynamic model is constructed and utilized to illustrate the interactions of several primary dynamic ecologic and economic relationships that are important in effective rangeland management. Within this context, the implications of various range management strategies are explored.

The management of agroecosystems by agricultural producers depends on ecological as well as economic relationships. Rykiel pointed out that, to an ecologist, economic decisions often "can appear ecologically irrational and self-defeating. To the agriculturist, on the other hand, ecologically reasonable decisions can appear economically illogical and even disastrous." This is often apparent in the management of rangeland for livestock production. The ecologist may find it irrational for the rancher to overstock at a rate that may cause a deterioration of the range condition. However, the rancher who is faced with a variety of economic constraints and incentives may find that it is in his personal best interest to overstock.

Optimal stocking rates of livestock on rangeland depend partly upon the perspective of the range manager. Hardin argued that on public rangeland individual cattlemen will want to stock as many cattle as possible, but, from society's perspective, this is not optimal stocking. Hardin insisted that public land used "in common" will be overused and ruined and that the only way to stop this is by restricting the land's use through public laws and regulations or by selling the land to private parties. Currently in the U.S. both approaches are used. About 46 percent of the nation's forest and rangeland is federally owned. The remainder is mostly privately owned but also includes some state and municipal land (U.S. Department of Agriculture, Forest Service).

While some economists argue that public rangelands could be better or more efficiently managed under private ownership (Shute; Baden and Stroup), others argue that private managers of rangeland tend to overuse the range. As can be seen in Table 1, on the average, rangeland in federal ownership is in better condition than rangeland not in federal ownership. This does not necessarily imply that managers of private rangeland are worse managers than managers of public rangeland. It may, at least in part, reflect differences in optimizing behavior between managers of public and private rangeland.

Optimal stocking rates on rangeland depend on the planning horizon and rate used to discount the value of future benefits from the range that are perceived to be appropriate. If it can be concluded that public rangeland should be managed for

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TABLE 1. Quantity and Condition of U.S. Rangeland[a] by Federal and Nonfederal Ownership, 1976.

	Condition Classes[b]				
Ownership	Good	Fair	Poor	Very Poor	Total
Federal[c]					
Million acres	40.7	106.5	59.8	10.3	217.3
Percent of total	18.7	49.0	27.5	4.8	100.0
Nonfederal[d]					
Million acres	55.7	97.0	184.8	95.6	433.1
Percent of total	12.9	22.4	42.7	22.0	100.0

Source: Provided by Pete Emerson and Gloria Helfand, The Wilderness Society. The data are also compiled by ecosystem and states by the U.S. Department of Agriculture, Forest Service.

[a] Land in the contiguous states on which the potential natural vegetation is predominantly grasses, grasslike plants, forbs, or shrubs.

[b] Condition classes refer to the degree of departure of the present vegetation from the ecological potential of the site. Good—rangelands on which present vegetation and soils are between 61 and 100 percent of the potential for the site. Fair—41 to 60 percent of potential. Poor—21 to 40 percent of potential. Very poor—20 percent or less.

[c] Includes 162.9 million acres of rangeland managed by the Bureau of Land Management and 54.4 million acres of rangeland managed by the Forest Service.

[d] All rangeland excluding the acreage managed by the Bureau of Land Management and the Forest Service.

the good of society as a whole, including future generations, and that society's planning horizon is longer than that of many individual cattlemen, and/or society's discount rate is lower than many individual cattlemen, then conflicts and differences between public and private management of rangeland will exist. Society may view individual cattlemen as being greedy exploiters of the range, while individual cattlemen may view public range managers as being over-zealous conservationists.

In addition, society views the use of chemical range improvement practices from a different perspective than many individual cattlemen. While society may view the extensive use of chemicals as risky and potentially harmful to wildlife, water sources, exposed humans, and the environment in general; individual cattlemen may want to use chemical range improvement practices whenever they are profitable. This paper illustrates the sensitivity of optimal stocking rates on rangeland to different planning horizons, discount rates, and the willingness to use, or profitability of, range improvement practices.

Modelling Framework

The ecological conditions that we use in this paper are those found in eastern South Texas bounded by the 36–44 precipitation-evaporation zone (Thornthwaite; U.S. Department of Agriculture, Soil Conservation Service, 1955). Range sites in the study area were evaluated and sites with deep soil profiles were grouped together (U.S. Department of Agriculture, Soil Conservation Service, County Soil Surveys). This group of range sites occupies approximately 89 percent of the rangeland within the study area (Godfrey *et al.*). Grouping range sites in this manner reduces site response variation from treatments because they have similar productive potentials (Workman *et al.*). The carrying capacity of these range sites under normal weather conditions is expected to vary from approximately 20 to 40 animal units per section. Within the study area, the ecology of the plant communities suggests that moderate levels of brush canopy comprised of multiple woody species occur at homeostasis where the carrying capacity is approximately 32 AU/section (Scifres *et al.*, 1983b).

In this study, a definition of carrying capacity is used as the state variable in a dynamic model of rangeland utilization. Without any brush control measures, the steady-state of 32 AU/section would be the maximum attainable level, although the range would support a higher stocking rate temporarily after some type of brush control. On the other hand, range conditions which would support only a lower stocking rate than 32 AU into perpetuity would be transitory if the stocking rate were sufficiently reduced, and the movement would be toward 32 AU as the steady-state. But each of these range conditions that will support a lower stocking rate than 32 AU can be defined quantitatively by the steady-state stocking rate which it would support. For the transitory range conditions resulting from brush control which would support more than 32 AU into perpetuity with some form of brush control, there is an associated steady-state stocking rate which could be maintained for the given range condition. Therefore, the state variable of this dynamic process is measured by the steady-state stocking rate which would maintain the given range condition as a steady-state, but this steady-state can be above or below the ecologically optimal steady-state of 32 AU. In the former case, some form of brush control would be required to maintain the implied steady-state, while no such action would be implied for the latter. This quantitative measure of range condition is referred to below as "carrying capacity."

Annual net returns to rangeland from livestock production are a function of the state of the rangeland, input and output prices, level of technology, cost effectiveness of range improvement treatments, and the rate at which the range is stocked. The impacts of prices and technology on annual net returns to the rangeland have been the subject of much previous research (Whitson and Scifres; Garoian *et al.*; Scifres; Shumway *et al.*). Dynamic relationships and interactions between range conditions, range improvement treatments, and net returns have been less thoroughly studied although widely recognized as important (Hopkin; Burt, 1971; Gray and Cox). For purposes of this study, prices and technology are held constant at 1982 levels. Annual net returns, therefore, are primarily a function of the range condition, actual level of stocking, and the cost of applying a range improvement treatment. It is assumed that the range manager will maximize the discounted value of a stream of expected net returns to the rangeland over a given planning horizon.

Previous research has indicated that under a continuous grazing system, when the range is stocked at approximately 150 percent of carrying capacity, all annual range forage is utilized (Kothmann and Mathis). Annual net returns also reach a maximum at this stocking rate at approximately 25 percent higher than if the range were stocked equal to its carrying capacity (Merrill and Miller). However, at a stocking rate greater than carrying capacity, the range deteriorates at a rate which increases with the degree of excess stocking (Stoddart *et al.*). Based on this information and data from the 1982 Texas Agricultural Extension Service budgets for cow-calf operations in South Texas, net returns to 640 acres were calculated across nine combinations of stocking rates and carrying capacities. Using these data the following net returns function was fitted using ordinary least squares regression:

$$NR_t = 84.5C_t - 2.115R_t^2 - 4.407C_t^2 + 6.35R_tC_t \qquad (1)$$

where:

NR_t = before-tax net returns to 640 acres in year t,
C_t = the carrying capacity of the range in year t, and
R_t = the actual rate that the range is stocked in year t.

Although this type of constructed data cannot be viewed as "statistical," all the coefficients are significant at the one percent level of probability, and R^2 equals 0.995 which suggests an adequate approximation.

As can be easily calculated from equation (1), annual net returns are maximized where $R_t = [6.35/(2)(2.115)]C_t = 1.5C_t$. Because the stocking rate affects the condition of the range in the future, the relationship between stocking rates, treatment application, and future carrying capacities must also be considered.

For the purposes of this paper, a range improvement treatment common to South Texas is used. The treatment involves aerial spraying in the spring of 2,4,5-T + Picloram, 1:1 ratio (0.5 pound active ingredient/acre) in alternate spray, no-spray strips that are crisscrossed in a grid pattern. This treatment suppresses the brush but does not eliminate it entirely, preserving wildlife habitat for white-tailed deer, dove, quail, turkey and javelina. The treatment reduces woody plant species and makes additional moisture, nutrients, and sunlight available for plant species more suitable for livestock production (Scifres and Polk). This results in a significant increase in forage production during the year of the treatment and the years immediately following (Scifres *et al.*, 1983a). Forage production then gradually falls as the woody plant species re-establish (Scifres *et al.*, 1977). This essentially instantaneous response of forage to treatment is in contrast to the pinyon-juniper problem of the Southwest analyzed first by Cotner, and later by Burt (1971), where the recovery begins slowly, reaches a maximum after several years, and then slowly declines.

The range's response to the treatment is approximated as follows. Application of the treatment is expected to increase the condition of the range to a carrying capacity of 40 AU/section (McBryde). When the range condition is very poor, the treatment may not be as effective; therefore, the treatment will be applied only when the carrying capacity of the range is greater than or equal to 30 AU/section. It is estimated that, if after the treatment the range is stocked at the ecologically optimal carrying capacity, the carrying capacity of the range will fall from 40 to 32 AU/section in approximately 8 years (Conner *et al.*). This time is assumed to be reduced to 4 years if the range is overstocked at 150 percent of carrying capacity (Scifres).

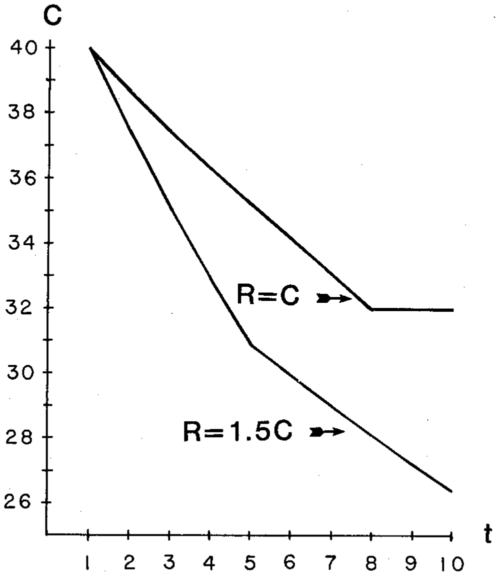

Figure 1. Carrying Capacity Over Time.

The above relationships are illustrated in Figure 1. If the treatment is applied in year 1, C_1 will equal 40 AU/section. When the range is stocked at carrying capacity, the carrying capacity will fall to 32 AU/section and then level off. If the range is stocked at 150% of carrying capacity, the carrying capacity will decrease to 32 AU/section approximately twice as quickly and then will continue to fall at a slower rate. The "kink" in the range response path over time reflects that a moderate brush canopy level of multiple woody species has encroached and is at homeostasis where the stocking rate and carrying capacity are approximately 32 AU/section (Scifres *et al.*, 1983b). While the true range response to the treatment over time is considerably more complex, this linear approximation is sufficient to illustrate the effect that a viable range improvement practice can have on optimal stocking rates over time. Using these assumptions, information discussed, and the functional relationships expressed in equation (1) above, the following dynamic decision model is constructed:

$$\text{MAX:}\quad NPV = \sum_{t=1}^{N} (NR_t - T_tK)(1 + r)^{-t} \qquad (2a)$$

with respect to $\{T_t\}$ and $\{R_t\}$, subject to:

$$T_t = \begin{array}{l} 0 \text{ when } C_t < 30\text{, else} \\ 0 \text{ or } 1, \end{array} \qquad (2b)$$

$$C_t = \begin{array}{l} 40 \text{ when } T_t = 1\text{, else} \\ BC_{t-1} - 2.26(R_{t-1} - C_{t-1})/36, \end{array} \qquad (2c)$$

$$B = \begin{array}{l} 0.9686 \text{ when } C_{t-1} > 32\text{, else} \\ 1, \end{array} \qquad (2d)$$

$$C_t \geq 0\text{, and} \qquad (2e)$$

$$R_t \geq 0. \qquad (2f)$$

where:

NPV = the value of the discounted stream of expected returns to a section of rangeland from year 1 to year N,

NR_t = annual net returns as a quadratic function of C_t and R_t as expressed in equation (1),

T_t = a binary variable that equals 1 when the treatment is applied and equals 0 when the treatment is not applied,

K = the adjusted cost of applying the treatment to a section of rangeland in the spring, and

r = the discount rate.

Equation (2a) expresses the objective of maximizing discounted net returns minus the cost of applying the treatment. Equation (2b) states that the treatment will not be used when the carrying capacity of the range is less than 30 AU/section because the treatment is not efficacious in that region. Equations (2c) and (2d) state the relationships between the carrying capacity of the range, the treatment, and the previous year's carrying capacity and stocking rate.

Model Solutions

Solutions of the model are calculated for 5 scenarios. Brief descriptions of these scenarios are given in Table 2. Scenario one assumes that the range manager has a one-year planning horizon and each year the range is simply stocked to maximize single year net returns regardless of effects on future range conditions. The carrying capacity in year 1 equals 32 AU/section.

Scenario two assumes that the range manager has a ten-year planning horizon and the manager maximizes the stream of discounted net returns to the range. The discount rate is assumed to be 5 percent. Carrying capacity of the range in year 1 equals 32 AU/section, and the manager is unable or unwilling to use the treatment.

Scenario three assumes that the manager has an infinite planning horizon and maximizes the value of the stream of discounted net returns to the range into perpetuity. The discount rate is assumed to be 5 percent. The carrying capacity of the range in year 1 equals 32 AU/section, and the manager is unable or unwilling to use the treatment.

Scenario four is identical to scenario three except the discount rate is assumed to be 10 percent.

Scenario five also assumes that the range manager has an infinite planning horizon and maximizes the value of the stream of discounted net returns to the range into perpetuity. The discount rate is assumed to be 5 percent. The manager is willing and able to use the treatment. The cost of the treatment is assumed to be \$2,560/section.

The solution to the model under scenar-

TABLE 2. Brief Descriptions of the Five Scenarios.

Scenario	Planning Horizon	Discount Rate	Treatment Status
1	1 year	5%	Not Used
2	10 years	5%	Not Used
3	∞	5%	Not Used
4	∞	10%	Not Used
5	∞	5%	Used

TABLE 3. Summary Solutions of the Five Scenarios.

Scenario	C_1	C_{10}	R_1	R_{10}	NR_1	NR_{10}	$\sum_{t=1}^{10} NR_t$	$\sum_{t=1}^{10} (NR_t - T_tK) \cdot (1+r)^{-t}$
1	32	24	48	36	3,066	2,235	26,295	20,591
2	32	25	46	37	3,059	2,285	26,619	20,820
3	32	32	32	32	2,524	2,524	25,238	19,488
4	32	30	36	33	2,760	2,557	26,547	16,420
5	40	31	59	46	3,943	2,961	34,343	20,325

io one is easily calculated. The stocking rate in each year will equal 1.5 times the carrying capacity of the range in that year. Based on the model, stocking rates, carrying capacities, and net returns are calculated sequentially over time.

The solution under scenario two is calculated using a quadratic programming (QP) package developed by Cutler and Pass. The objective function in equation (2a) is quadratic in form, and equations (2c) through (2f) express a system of linear constraints. For a finite planning horizon this model can be solved with QP.

The solutions to the model under scenarios three and four are calculated based on an approximate decision rule presented by Burt and Cummings. Burt (1981) and Pope *et al.* successfully used this methodology with similar models dealing with soil conservation.

The solution of the model under scenario five is calculated as follows: Let J(L) equal the discounted annual net returns minus the cost of the treatment from year 1 to year L. Also let the discounted value of the stream of expected returns to the rangeland from year 1 to ∞, when the treatment occurs every L years, equal G(L) where:

$$G(L) = J(L) + J(L)/(1+r)^{L} + J(L)/(1+r)^{2L} \ldots \quad (3a)$$

$$= J(L) \sum_{P=0}^{\infty} 1/(1+r)^{PL} \quad (3b)$$

$$= J(L)/(1 - 1/(1+r)^{L}). \quad (3c)$$

Using the QP package by Cutler and Pass, the stocking rates that maximize J(L) and the corresponding values of J(L) are calculated for integer values of L between 1 and 10. Then, using equation (3c), the value of L that maximizes G(L) is determined.

The principal attraction of the QP and the Burt and Cummings methodology used in this study to solve the model is ease of application. Although a more efficient way to solve the dynamic optimization problem is a numerical algorithm based on dynamic programming (Bellman and Dreyfus), this is a relatively unimportant consideration where the problem is small.

Results and Discussion

Carrying capacity of the range, actual stocking rate, and annual net returns are given for years 1 and 10, for each of the scenarios, in Table 3. The sum of annual net returns and the sum of discounted net returns minus treatment costs over a ten-year period are also given in Table 3. In Figure 2, net returns under each of the five scenarios are plotted over ten years.

In scenario one, where the planning horizon is only one year, overstocking results in a depletion in range condition such that the carrying capacity of the range drops by approximately 25 percent in ten years. As a result of this depletion, net returns to the rangeland fall by approximately 27 percent in ten years.

In scenario two, where a finite planning

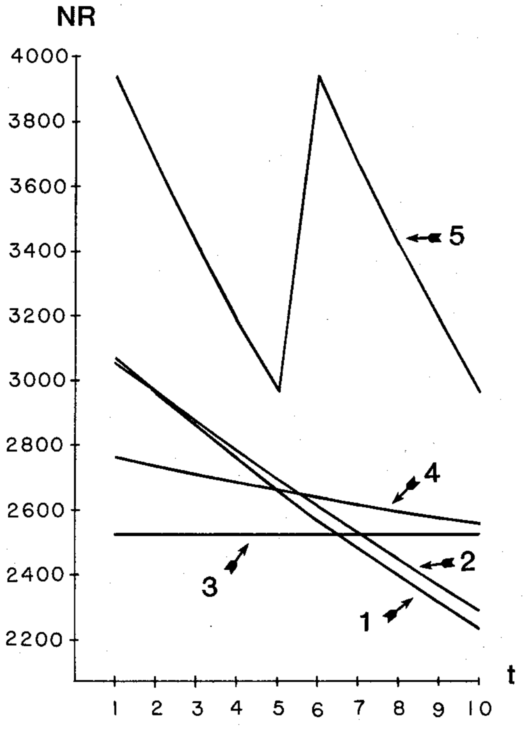

Figure 2. Net Returns over Time.

horizon of ten years is assumed, the results are similar. However, the range is not stocked quite as heavily, and the condition of the range deteriorates at a slightly slower rate.

In scenarios three and four, an infinite planning horizon is assumed. Because no range improvement practice is used, the only way to maintain the current level of range condition and net returns is through proper stocking. A biological equilibrium is defined by the model where the actual stocking rate equals the carrying capacity and is less than or equal to 32 AU/section. Any carrying capacity between 0 and 32 can be a biological equilibrium. However, for a given discount rate, there is only one economic equilibrium level.

In scenario three, where the discount rate equals 5 percent, the optimal stocking rate and economic equilibrium are defined where R = C = 32. Given the kink in the difference equation at C = 32, this is true for all discount rates less than or equal to 6.38 percent (2.26/36). For discount rates greater than 6.38 percent, the economic equilibrium is monotonically declining as the discount rate increases. In scenario four, for example, where the discount rate equals 10 percent, stocking rates initially are greater than the carrying capacity. The condition of the range gradually deteriorates over time, and stocking rates fall until an economic equilibrium is reached where R = C = 22.7.

The kink in the difference equation defines the maximum carrying capacity that can be maintained through proper stocking. Scenarios three and four illustrate that with an infinite planning horizon and low discount rates, the economic equilibrium is at that point. At relatively high discount rates, initial overstocking of the range will result in an economic equilibrium at a point below the maximum carrying capacity that can be maintained through proper stocking.

In scenario five, the treatment is used every 5 years. The optimal management plan, in terms of livestock production, is to systematically overstock the range and periodically apply the treatment.

These results illustrate some of the principal reasons for significant disagreement about the level of stocking of rangeland for livestock production. Many range scientists, ecologists, and managers of public rangeland, who view that rangeland should be managed for the good of society as a whole, may see the relevant planning horizon for range management as being infinity and the appropriate discount rate as relatively small. To them stocking rates in excess of the optimal ecological rate ("overstocking") are illogical because they reduce future rangeland productivity. Even if economically viable range improvement treatments exist, overstocking significantly reduces the life of its effectiveness. This fact may cause a reluctance to accept systematic overstocking.

For others the incentives to overstock are real. Many ranchers may have relatively short planning horizons. They may be very uncertain about the effects of management decisions on future productivity, and therefore, they may simply worry about maximizing current returns. They may also have large current economic commitments, such as mortgages, or they may simply be shortsighted. Regardless of the reason, ranchers with relatively short planning horizons and/or high discount rates will want to overstock.

Even range managers who have an infinite planning horizon and a low discount rate may view overstocking of rangeland as being appropriate if economically viable range improvement practices exist or are expected to become available in the future. The value of net returns from rangeland will be higher when it is systematically overstocked and improvement treatments are periodically applied. The cheaper and more effective the treatments are, the higher the stocking rate and frequency of treatment application will be.

Conclusions

Economic pressures are a part of human ecology. As humans interact with the natural environment, these pressures influence decisions relating to management of natural resources. This is nowhere more clear than within the context of rangeland management for livestock production. From an ecologic perspective, stocking rates under a continuous grazing system should never exceed the carrying capacity of the range as determined by range scientists. The range manager who attempts to maximize short-run annual net returns to the range may desire to stock at much higher rates.

Over an extended time period, the manager who takes this shortsighted approach may cause deterioration of the range condition so that annual net returns become lower than they would have been if the range had not been overstocked. In the scenarios illustrated in this paper, this occurred after only 6 or 7 years. If economically viable and ecologically sound range improvement treatments are available, a range management strategy that systematically "overstocks" and periodically applies treatments would be more profitable.

In conclusion, the model constructed and utilized in this paper illustrates interactions of several primary dynamic ecologic and economic relationships that are important in effective rangeland management. One notable exception, however, is weather variability and its effect on both annual net returns and range condition over time. Consequently, results from this model are deterministic and must be interpreted as such. Future research dealing with development of dynamic models relating to effective rangeland management that incorporates uncertainty due to variable weather conditions is also needed.

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