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ANALYSIS

Economic implications of maintaining rangeland ecosystem health in a semi-arid savanna

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ABSTRACT

A simulation model was used to determine the ecological and economic consequences of managing stocking rate on semi-arid savanna rangeland continuously stocked with livestock to achieve the alternate management goals: (1) maintaining current range condition, (2) maximizing profit, or (3) improving range condition over a 30-year time frame. We developed values for end of the year herbaceous standing crop and utilization required to attain these management goals for rangeland in poor to excellent condition. Based on extensive field research conducted in this region over 5 decades, range condition in this model is programmed to decline in response to three factors: excessive grazing pressure, below average precipitation, and an increase in woody plants. Earning capacity is four times higher for range in excellent condition than that in poor condition. For all initial range condition (RC) values, simulated stocking rates that maintained RC resulted in simulated mean weaning weights 93-94% of maximum. Maximum short-term and long-term profit is attained at higher stocking rates than would maintain long-term range condition and at much higher levels than would increase range condition levels. When stocked for maximum profit, individual animal performance was 90% of maximum. The model predicts that low stocking rates allow range condition to improve. At these recovery stocking rates, total 30-year profits were found to be 78%–87% of the stocking rates that would maintain range condition, and only 67%–75% of stocking rates that would maximize profit. Predictions of the end of year standing crop to maintain range condition were in broad agreement with the 1000 kg ha^{-1} advised for this region. To improve range condition, the model predicts that an end of year standing crop of 1500–2000 kg ha^{-1} is required, compared to the generally advised level of 1200–1500 kg ha^{-1}. The predicted end of year forage standing crops for the maximum profit goal are well below the advised 800 kg ha^{-1} threshold required to prevent degradation for all of the initial range conditions that were simulated. To ensure maintenance of range in excellent condition, our results concur with the advised utilization levels of 20–25%. However, for range in poorer than excellent condition, the model predicted much lower utilization levels were needed to maintain or improve range condition.

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1. Introduction

Rangelands are semi-natural ecosystems that cover large proportions of Africa, Asia, Australia and the Americas. They provide ecosystem services upon which the well-being of current and future human societies is predicated. These services include maintenance of stable and productive soils, delivery of clean water, and sustaining plants, animals and other organisms that support the livelihoods and aesthetic and cultural values of people living in rangelands (Daily, 1997; Grice and Hodgkinson, 2002). Around the world, people living on rangelands have frequently obtained productive output from them by grazing domestic livestock.

The grazing ecosystems of prehistory were ecologically stable since grasslands and wild ungulates coevolved and coexisted for tens of millions of years since the late Mesozoic era. The replacement of free-ranging wild herbivores with livestock whose movements are restricted by man has not emulated the impact of wild ungulates (Frank and McNaughton, 2002). Specifically, the more persistent and concentrated use of vegetation by domestic animals managed by sedentary humans removes the key stabilizing element of intermittent rest from herbivory and increases the risk of overgrazing. Excessive grazing has frequently resulted in a cascade of effects starting with dramatic shifts in plant species composition and leading to accelerated soil erosion, reduced soil and hydrologic function, and lower primary and secondary production. The maintenance of artificially high animal numbers through supplementary feeding during less productive periods has further exacerbated degradation (Oesterheld et al., 1992; Milchunas and Lauenroth, 1993). Consequently, there has been considerable debate about the importance of removing livestock from rangelands to remedy this degradation. However, because rangelands co-evolved with wild herbivores, maintaining plant species composition in many rangelands also requires periodic herbivory. Removing livestock entirely may have unintended effects such loss of herbivory-dependent key species, lower biodiversity and reduced nutrient cycling with negative consequences for ecosystem function and the people whose livelihoods depend on livestock production (Pieper, 1994; Olff and Ritchie, 1998).

As rangeland ecosystems provide important services, such as the delivery of clean water, that are critical for well-being of human society, it is important for those making a living on the land to adopt management practices that maintain or restore rangeland ecosystem health and resilience (Kessler et al., 1992). Therefore, assessing the economic efficiency of ecologically sound land management practices is important both for the individual landowner and society at large. It is widely recognized that to maintain ecological functionality and the delivery of ecosystem services in rangelands, land managers must actively avoid excessive rangeland degradation (Heitschmidt and Taylor, 1991; Oesterheld et al., 1992; Milchunas and Lauenroth, 1993; Holechek et al., 2001; Wessels et al., 2007). In this context, climatic forces substantially affect rangeland ecosystems because precipitation, the principal determinant of annual net primary production (ANPP), varies markedly and stochastically within and between years. Consequently rangeland managers must develop strategies to deal adequately with variability and uncertainty in forage supply (Doren et al., 1985; Kothmann and Smith, 1983).

Overstocking is considered the primary cause of rangeland deterioration because deleterious shifts in vegetation composition may occur when consumption by herbivores exceeds the productive capacity of plants during periods when natural resources are scarce, such as drought (Van de Koppel and Rietkerk, 2000; Higgins et al., 2007; Wessels et al., 2007). The choice of appropriate stocking rate is crucial in order to achieve desirable animal performance while maintaining or improving the condition and productivity of rangelands (Díaz-Solís et al., 2006; Teague et al., 2008). The choice of stocking rate is also important to ensure that adequate fine fuel is available to regularly apply prescribed fire in order to economically control the proliferation of woody plants (Perrings and Walker, 1997; Ansley and Jacoby, 1998; Higgins et al., 2007; Teague et al., 2008). In most savannas, woody plant proliferation increasingly suppresses herbaceous production and changes herbaceous species composition, leading to lower primary and secondary productivity (Higgins et al., 2007; Teague et al., 2008). In place of prescribed fire, chemical or mechanical treatments be used to control woody plants but they are generally more costly (Teague et al., 2001).

In Texas, net economic returns from rangeland-based beef cattle enterprises are often marginal and the common recommendation for improving profitability is to maintain low production costs rather than to improve productive performance of cattle (Doren et al., 1985; Turner and Ducoing, 1998). Generally, successful cow-calf producers operating in drought-prone environments rely on two pervasive management practices: (1) appropriate stocking rate management and (2) controlled, properly timed, calving and breeding seasons that coincide with expected availability of forage (Kothmann and Smith, 1983).

Given that the assessment of the economic efficiency of ecologically sound land management practices has implications for society at large, the aim of our study is to use a simulation model to determine the ecological and economic consequences of managing stocking rate on a savanna rangeland to achieve one of three management goals. These include: (1) maintain range condition, (2) maximize profit, or (3) improve range condition over a 30-year time frame. Here, “range condition” encompasses overall ecosystem functional integrity and productivity. To provide a practical guide for field managers, the model is also used to develop values for key field parameters required to attain each management goal under different range conditions: year-end herbaceous standing crop and utilization.

The model we use is Simple Ecological Sustainability Simulator (SESS), which is capable of assessing rangeland ecosystem and economic responses to stocking rate changes (Díaz-Solís et al., 2003, 2006; Dube, 2005; Teague et al., 2008). It has been parameterized and corroborated using systems level data derived from large scale research projects conducted since 1955 on working ranches in the Rolling Plains, where our study is located.

2. The study system

The climate in the Rolling Plains eco-region is continental with an average of 220 frost-free growing days. Mean annual precipitation is 648 mm that is bimodally distributed with peaks in May (95 mm) and September (76 mm) but significant precipitation can be expected during any month. Mean monthly temperatures vary from 3.9 °C in January to 36.4 °C in July.

The woody vegetation consists primarily of mesquite (*Prosopis glandulosa* Torr.) savanna with trees up to 5 m in height and a low density of the shrub lotebush (*Ziziphus obtusifolia* (Hook. Ex. Torr. & A. Gray) and cactii (Opuntia spp). These woody species are not palatable to livestock or wildlife except for mesquite pods which are an important part of the diets of several mammalian species in late summer. The herbaceous vegetation is dominated by a cool season (C_3) perennial, Texas wintergrass (*Nassella leucotricha* Trin.&Rupr.), the warm season (C_4) perennials silver bluestem (*Bothriochloa laguroides* DC.), sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.), meadow dropseed (*Sporobolus compositus* (Poir.) Merr.), buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.), the C_3 annual Japanese brome grass (*Bromus japonicus* Thunb. Ex Murray), and the warm season forbs western ragweed (*Ambrosia psilostachya* DC.), annual broomweed (*Gutierrezia texana* (DC.) Torr. & A. Gray) and heath aster (*Aster ericoides* L.).

The primary land use on rangeland in the area is beef cattle production, principally cow-calf systems (Teague et al., 2001). Cows usually calve in January to March and calves are weaned in October or November. Warm season grasses provide most of the herbaceous production while cool season grasses provide forage whose availability and nutritive value (protein content and digestibility) is adequate to reduce supplementary food costs (Teague et al., 2001). Income from wildlife based enterprises is increasingly important (Bernardo et al., 1994).

Neglecting to reduce mesquite brush and cactus has a major negative impact on range condition, secondary productivity and profitability (Teague et al., 2008). This threatens the sustainability of livestock ranching and wildlife and grassland bird habitat (Knopf, 1994; Rollins and Cearley, 2004). Although many wildlife species require woody plant cover, the reduction in warm season grasses and forbs in response to increasing mesquite cover negatively affects many grassland game and non-game species. Regular application of prescribed fire or other more expensive treatments to reduce mesquite and cactus is necessary to maintain or improve range ecosystem function and productivity and sustain livelihoods (Hamilton and Ueckert, 2004).

3. Brief model description

The model we use to conduct our analysis was developed for north Texas mesquite-grass communities with 600–700 mm precipitation to analyze herbaceous and woody vegetation dynamics in response to grazing and burning management strategies (Teague et al., 2008). It was based on SESS, which was originally developed for north México and south Texas rangeland (Díaz-Solís et al., 2003, 2006) and modified for north Texas by Dube (2005). SESS is a compartmental model based on difference equations with a one month time-step and is programmed in STELLA® 9.0 (High Performance Systems, Inc., Hanover, New Hampshire). The major sub models of the SESS model are diagrammatically presented by Teague et al. (2008).

SESS simulates forage production, range condition, diet selection and beef cow-calf production. The concept of rainfall-use-efficiency (RUE, kg aboveground dry matter [DM] ha^{-1} mm^{-1} of precipitation year^{-1}) proposed by Le Houreou (1984) was used to calculate monthly above-ground net primary productivity (MNPP, kg DM ha^{-1} year^{-1}) resulting from the amount of monthly precipitation (PPT, mm month^{-1}). Based on field work conducted in this area, a maximum amount for MNPP was set at 1200 kg ha^{-1} year^{-1} to compensate for unusually large rainfall events that overestimate monthly forage growth when using the RUE approach, since much of the rainfall in these large rainfall events runs off and does not produce herbaceous growth (Wilcox et al., 2006). The dynamics of green and dry standing crop are represented in the forage submodel. Green standing crop is converted to dry standing crop via senescence and frost. Green and dry standing crop biomass decline due to consumption, trampling, dung deposition and decomposition. The diet selection submodel estimates the proportions and amounts of green and dry forage in the cattle diet based on preference and harvestibility, as described by Blackburn and Kothmann (1991).

Range condition (RC) represents the productivity, health and composition of the herbaceous vegetation to provide an index of ecological functional integrity. Range condition class is quantified on a relative scale to represent rangeland as: Excellent (RC=1.25), Good (RC=1.0), Fair (RC=0.75), and Poor (RC=0.50) condition. It is increased or decreased according to the proportion of ANPP consumed by the cattle, or utilization, which is the percentage of ANPP consumed by cattle each year as outlined by Díaz-Solís et al. (2003). In addition, when mesquite increases, herbaceous plant species composition changes and forage production declines, which effectively decreases range condition as defined by Holechek et al. (2001). Consequently RC is decreased in the model to represent the effect of mesquite expansion on herbaceous composition and forage productivity (Ansley et al., 2004; Teague et al., 2008). Quantitatively this is expressed as:

$$WP\ effect\ on\ RC = 0.00175 - (0.000006 \times WP)$$

where WP is total woody canopy plant cover as a percentage of the total land area.

Range condition can also decrease as a consequence of below average precipitation (Teague et al., 2004). In the model RC is decreased by 10% at the end of summer if forage standing crop is less than 800 kg ha^{-1}. This function was based on declines in perennial grass basal cover measured at this location (Teague et al. (2004). In the model this adjustment is made prior to burning so that the effect of burning will not be a factor in making the adjustment to RC as outlined in Teague et al. (2008).

The growth of woody plants and cacti and their associated influence on herbaceous vegetation is simulated, along with control of these undesirable plants through the regular use of prescribed fire (Teague et al., 2008). The cattle production submodel simulates DM intake, cow body condition score, herd pregnancy rates, and calf growth to weaning as detailed

Table 1 – The variability (mean±standard deviation) of stocking rates and 30-year NPV revenue ($ * 1000) for each initial range condition to achieve the 3 different management goals using 20 replicates of rainfall data having the same mean and pattern of variation as the historical rainfall data used in the simulations

Initial range condition	Management goal					
	NPV_{max}		RC_{maint}		RC_{max}	
	Stocking rate (AUY 100 ha^{-1})	30-year NPV ($ * 1000)	Stocking rate (AUY 100 ha^{-1})	30-year NPV ($ * 1000)	Stocking rate (AUY 100 ha^{-1})	30-year NPV ($ * 1000)
1.25	52.7±8.95	1191±241	31.6±2.32	939±139	31.6±2.32	939±139
1.00	28.8±2.64	747±117	24.1±2.02	703±102	17.7±0.78	617±61
0.75	17.4±1.88	525±89	13.9±1.64	491±57	9.8±0.49	429±30
0.50	5.6±3.41	283±59	2.0±2.22	208±87	0.9±1.14	183±69

by Díaz-Solís et al. (2003). Stocking rate is calculated on an Animal Unit basis (1 AU=450 kg cow) and consumption varies according to body mass and physiological state. Calves are not considered to graze forage but the increased forage consumption of their dams is taken into account by increasing consumption according to milk production. Stocking rate is adjusted to include the biomass of bulls at 1 bull (=1.25 AU) to 25 cows.

An economic submodel calculates annual profit or loss and the net present value (NPV) for different management strategies (Teague et al., 2008). Income from wildlife is included in the model at a rate of $12 ha^{-1} $year^{-1}$ based on average hunting lease revenue (2000 to 2005) for leased cow-calf ranchland in the Rolling Plains of Texas (Bevers pers. Comm.[1]). Parameter names, symbols and units for descriptors and variables added to the original SESS model are listed in Appendix A.

The modified SESS model was parameterized and output was corroborated with research data obtained over the last 55 years at the systems level from large-scale research projects on working ranches (Teague et al., 2008). The modified SESS model has been shown to reliably model grassland ecosystem processes and beef cow-calf production under different grazing practices and strategies for long-term (20–50 years) simulations of semi-arid grass rangelands in north Mexico and south Texas (Díaz-Solís et al., 2003, 2006), and semi-arid mesquite-grass rangelands in north Texas (Dube, 2005; Teague et al., 2008).

4. Materials and methods

In this paper we calculated the opportunity cost due to not having range in excellent condition, and that of improving RC back to excellent condition over the 30-year simulations. We used SESS to simulate changes in range condition and NPV over 30-year periods for range initially in poor, fair, good or excellent condition, using a wide range of stocking rates for each of these four initial range condition (IRC) categories. For each IRC we simulated: (1) secondary production measured by live weight of weaned calves sold, (2) accumulated 30-year NPV ($), and (3) the stocking rates required to achieve each of three alternative objectives: maintain RC, maximize RC over 30 years or achieve the highest accumulated 30-year profit (NPV).

The model is also used to assess how different goals can be achieved by modifying stocking levels based on timely monitoring of key field parameters. For each IRC, the model simulates the herbaceous standing crop that must remain at the end of the year, and the utilization required to achieve each of the management goals. Stocking rate acutely influences the vigor and composition of vegetation, the profitability of ranching enterprises, the quality of habitat for wildlife, soil integrity, and hydrology (Heitschmidt and Taylor, 1991; White and McGinty, 1992; Hanselka and Landers 1993). Since the inception of the range management profession, selection of the "optimal" stocking rate has been a basic challenge for managers of grazing land (Holechek et al., 2001). Numerous methods have been developed to assist in estimating appropriate stocking rates to maintain or improve the health and composition of the vegetation (Dyksterhuis, 1975; USDA-SCS, 1975; White and Richardson, 1991; White and McGinty, 1992; Ranching Systems Group, 1993; USDA-NRCS, 1997; Kothmann and Hinnant, 1999). These methods are based on an inventory of herbaceous plant biomass, which is converted to animal unit days (AUDs) of grazing available based on a specified set of assumptions regarding utilization levels. We used our model to predict the values of these parameters that will achieve each of the three previously stated management goals.

Income from wildlife is included at $12 ha^{-1} $year^{-1}$ for all simulations since it is a major source of recreational income to land managers. However, in tall- or mid-grass prairies, fair to good range condition is considered optimal for bob-white quail, while either excellent or poor condition are sub-optimal (Guthery, 1986; Baker and Guthery, 1990). If quail hunting is a significant part of the management goal, then fair to good RC would be desired, and the associated increase in income would mitigate the loss of livestock or wildlife related earnings when RC drops below excellent. We simulate increased quail hunting income for range in fair and good condition to evaluate the impact this could have to 30-year ranch profit.

All simulations had the following in common: (1) The same 30-year mean monthly precipitation from 1970 to 2000 for Wilbarger County in north Texas, (2) cows are bred to calve in February and March, (3) cattle mortality occurs each month as a function of body condition, (4) cows that are not pregnant at weaning in October or have died are replaced in November, (5) the calculation of stocking rate includes all cows, bulls, and

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nursing calves, and (6) prescribed fire is applied every 8 years to maintain low levels of woody plants and cactii with pre- and post-fire foraging deferment as described in Teague et al. (2008).

In semi-arid regions rainfall is highly variable both within and between years (Le Houreou, 1984). We ran the model using 20 replicates of 30-year rainfall data that had the same mean and pattern of rainfall to determine the variability of model output as a result of rainfall variability. We randomly generated twenty replicates of 30-year rainfall data using a random generator that gave a random sequence of the historical annual rainfall for Wilbarger County, Texas used in this simulation exercise. Monthly rainfall in each year was not changed but the order of years was randomized for each of the 20 replicates of 30-year data.

The simulated means using 20 replicates of different rainfall data with the same means and intra-seasonal patterns are presented in Table 1. These means are very close to the means generated from the historical rainfall from 1970 to 2000 used in this simulation exercise (cf. Table 1 with Table 4). Standard deviations as a percentage of the mean generally varied from 7 to 15%. The exceptions were for the initial range condition of 0.5 which were considerably more variable. Since the means from the 20 replicates were very close to those from the historical data set and deviations were generally relatively small, we completed the simulations using the historical rainfall data set.

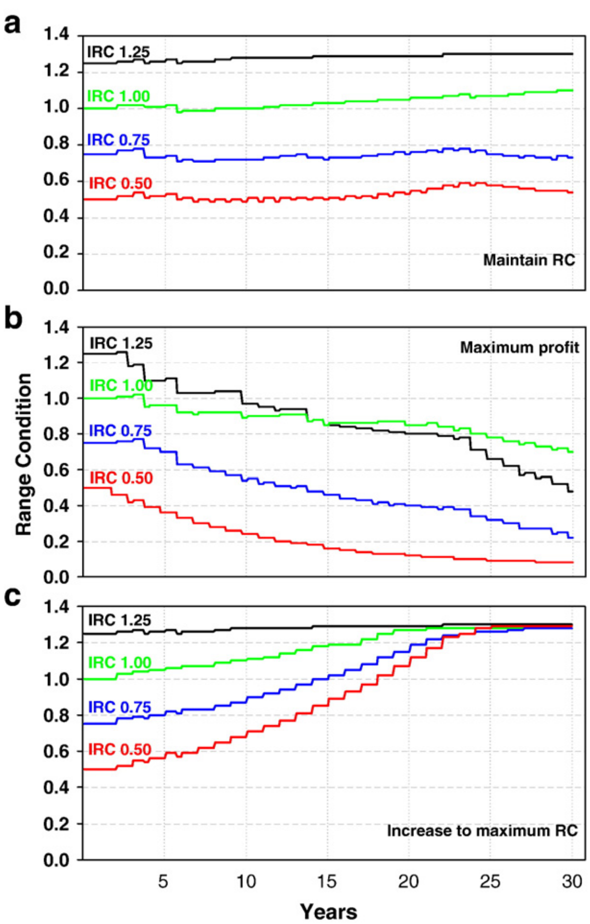

Fig. 1 – Changes in range condition with different initial range conditions (IRC) values when stocked to achieve: (a) maintenance of range condition, (b) maximum profit, or (c) an increase to maximum range condition over the simulation period of 30 years.

Table 2 – The stocking rates (AUY 100 ha^{-1}) required for each initial range condition to achieve maintenance of range condition (RC_{maint}), reach the maximum range condition (RC_{max}) or achieve maximum profit (NPV_{max}) over a 30-year period

Initial range condition	Management goal		
	NPV_{max}	RC_{maint}	RC_{max}
1.25	50	31	31
1.00	26	24	15
0.75	18	13	8
0.50	6	2	1

5. Scenario analyses

5.1. *Range condition dynamics for different management goals*

When stocking at appropriate levels to maintain range condition (RC_{maint}), or to increase range condition to maximum (RC_{max}), or to achieve maximum profit over the 30-year simulation period (NPV_{max}), the dynamics of range condition differ widely for different IRCs (Fig. 1). The stocking rates required to achieve each goal for all IRC values are given in Table 1. Model simulations indicate that stocking rates that would produce NPV_{max} are higher than those that would lead to the maintenance of RC at IRC (RC_{maint}) and are much higher than those required to increase RC levels to excellent range condition (RC_{max}) (Table 2).

When each IRC is stocked to maximize NPV, the consequent rate of decline in RC over the 30-year simulations differs for each IRC (Fig. 1b). The rate of decline for IRCs$\leq$1.00 is similar over time, while the decline for IRC=1.25 is much steeper. Although range in excellent condition allows for higher stocking rates because of the greater abundance and productivity of preferred herbaceous plants, the level of stocking is so high (NPV_{max}=50 AUY 100 ha^{-1}) (Table 2) that further stocking at this rate leads to a more rapid deterioration in RC than for good, fair and poor IRCs, which have much lower stocking rates. This more rapid decline in RC of $IRC_{1.25}$ emphasizes that, regardless of the prevailing RC, it is necessary to adequately monitor key parameters in order to make timely adjustments to stocking rates so as to avoid perpetuating management that degrades the resource base.

From an economic perspective, these issues can be considered with respect to 'natural capital' and dividends resulting from this capital. Improving RC to excellent necessitates reducing stocking rates. Economically, this represents a deferment in reduction in short-term income in exchange for increasing the natural capital of the production system due to the elevated productive capacity represented by increased RC. The dividends of this heightened productive capacity can be converted to income by increasing the stocking rate at a later point in time. However, if it is excessive, this subsequent increase in use of vegetation can lead to a decline in the elevated natural capital. The key for excellent condition is to only use the 'dividend' of the production system and not consume the capital. Reducing SR to increase RC results in 'investment of the dividend' back into the principal 'capital', which is represented as improving RC.

5.2. *Earning capacity of range in different condition*

Productivity levels, and hence the earning capacity, varies widely according to rangeland condition. Fig. 2 illustrates the effect of increasing stocking rate on simulated mean weaning weight and per hectare live-weight production of calves from rangeland in excellent, good, fair and poor condition. These relationships take into account the negative and positive effects of stocking rate on RC (shown in Fig. 1) and subsequent modifications to the productivity of the range. Primary and secondary productivity differ markedly according to RC. Our simulations show that the annual mean 30-year live weight of calves in a cow-calf enterprise varied from 45 kg ha^{-1} for range in poor condition to 150 kg ha^{-1} for range in excellent condition (Fig. 2).

These differences in productivity (i.e., interest on ecological capital) allow for higher stocking levels and consequently greater profit with increasing RC (Fig. 3; Table 3). In Fig. 3, the range condition plotted is the RC at the end of the 30-year simulation in response to each stocking rate. At lower stocking rates the final RC is higher than the initial RC since at low stocking rates RC increases (e.g., reinvesting dividends) over

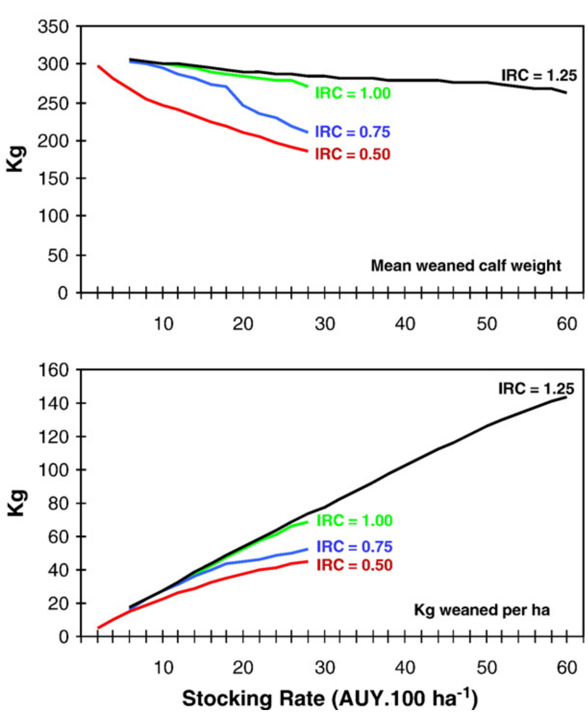

Fig. 2 – Changes in mean weight of weaned calves (kg) and the live weight weaned per hectare (kg ha^{-1}) at different stocking rates for initial range condition (IRC) values.

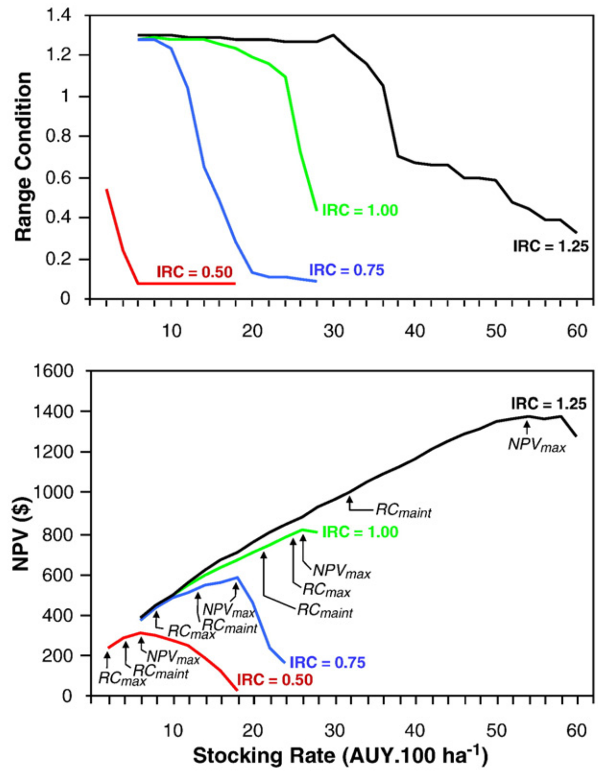

Fig. 3 – Changes in final range condition and the net present value (NPV) at different stocking rates for initial range condition (IRC) values. The stocking rate required to achieve maximum profit is indicated by NPVmax for each IRC simulated. Final RC values at lower stocking rates in Fig. 3 are higher than IRC values since lower stocking rates allow RC to increase over the simulation period.

the simulation period. For all simulated IRC values, stocking rates that maintained IRC resulted in a mean weaning weight 93–94% of maximum mean weaning weight (See Table 3 and Fig. 2). This is consistent with range science economic theory which states that the optimum stocking rate lies somewhere between the stocking rate that results in maximum weight

Table 3 – The stocking rates required to achieve maintenance of range condition (RC_{maint}) and the associated 30-year NPV revenue ($ * 1000), and the influence of increasing hunting income on range in fair or good condition when stocking to achieve maintenance of range condition (RC_{maint}) and the associated 30-year NPV revenue ($ * 1000)

Initial Range Condition	Stocking rate (AUY 100 ha^{-1})	30-year NPV ($ * 1000)		
		Hunting income $12 ha^{-1} year^{-1}	Hunting income $18 ha^{-1} year^{-1}	% Increase
1.25	31	990	-	-
1.00	24	783	875	12
0.75	13	531	625	17
0.50	2	238	-	-

gains per animal and the stocking rate that results in maximum weight gains per hectare (Workman, 1986).

Total profit at stocking rates that will maintain IRC over 30-year simulations (RC_{maint}) varies from $238,000 to $990,000 with poor and excellent IRC values, respectively (Table 3). If assumed hunting revenues are increased by 50% for range in fair or good condition, which are optimal for bob-white quail, total profit over the 30-year simulations increase by 17 and 12%, respectively (Table 3). This is not considered for excellent or poor condition range, which are both considered sub-optimal as habitat for bob-white quail. Therefore, revenue from good and fair condition range could be increased by improving bob-white quail habitat and hunting more intensively (Guthery, 1986). However, while this strategy may partially offset the loss of revenue associated with range not being in excellent condition, it fails to fully recover such losses.

5.3. *Consequences of stocking for maximum profit*

Model simulations indicate that maximum profit (NPV_{max}) is attained at stocking rates that are higher than those that would maintain IRC levels (RC_{maint}) and at much higher than those that would lead to maximum RC (RC_{max}) (Fig. 3; Table 4). Final RC values at lower stocking rates in Fig. 3 are higher than IRC values, since lower stocking rates allow RC to increase over the simulation period as outlined in paragraph 5.2 above.

For range in excellent initial condition ($IRC_{1.25}$), RC is maintained at the initial level as stocking rate increases up to 32 AUY 100 ha^{-1} but it declines precipitously at stocking rates beyond this threshold level. However, NPV for $IRC_{1.25}$ continues to increase with increasing stocking rate reaching a peak at 50 AUY 100 ha^{-1} (Fig. 3) , at which point individual animal performance would be about 90% of maximum (Fig. 2). Similarly, for rangeland in good, fair and poor initial condition, the stocking rate that would maintain IRC is considerably less than that which would maximize profit (NPV), and in each case the corresponding individual animal performance would be approximately 90% of maximum. Clearly, monitoring of animal performance is inadequate to ensure the long-term maintenance of healthy and productive rangelands.

5.4. *Cost in lost revenue to improve range condition*

The model predicts that low stocking rates allow range condition to improve (Fig. 1) as documented in range science texts (Heitschmidt and Taylor, 1991; Holechek et al., 2001).

Table 5 – The loss in 30-year NPV revenue ($ * 1000) for managing to achieve maximum range condition (RC_{max}) or maintain range condition (RC_{maint}) or achieve maximum profit (NPV_{max})

Initial range condition	Differences in 30-year NPV ($ * 1000)		
	RC_{maint} – RC_{max}	NPV_{max} – RC_{max}	NPV_{max} – RC_{maint}
1.25	–	360 (73%)	360 (73%)
1.00	165 (78%)	205 (75%)	36 (96%)
0.75	103 (81%)	155 (73%)	52 (91%)
0.50	31 (87%)	104 (67%)	73 (77%)

Figures in parentheses indicate the percentage of revenue to be expected by following the alternate management goal.

Stocking rates that will allow rangelands to recover to excellent condition (RC = 1.25) over the 30-year simulation period were determined to be 15 AUY 100 ha^{-1} for IRC = 1.00, 8 AUY 100 ha^{-1} for IRC = 0.75, and 1 AUY100 ha^{-1} for IRC = 0.5 (Table 4).

At these recovery stocking rates, 30-year NPVs are 78% to 87% of those obtained at stocking rates that maintain RC (cf. RC_{max} and RC_{maint}) (Table 5). Earnings at recovery stocking rates are proportionately even lower when compared to earnings at stocking rates that maximize NPV; viz. 67% to 75% of NPV_{max} (cf. NPV_{maint} and RC_{max}). Similarly, when stocking to maintain IRC, NPV is only 77% to 96% of earnings at stocking rates that maximized profit (c.f. NPV_{max} and RC_{maint}).

A key objective of many ranchers is to increase profits from their rangeland-based enterprises. While they may change prior livestock management decisions to reach this objective, few monitor their primary resource or even consider how changes in livestock management will affect range condition. For example, a common option for maintaining a constant stocking rate under weather-related forage supply changes is to provide supplemental feed. Maintenance of artificially high animal numbers with supplementary feed during less productive periods, such as droughts, exacerbates range degradation because of intensified defoliation of preferred plants. Changes in plant species composition may occur if animal numbers are held constant when natural forage resources are scarce (Oesterheld et al., 1992; Milchunas and Lauenroth, 1993; Van de Koppel and Rietkerk, 2000). Clearly, if livestock numbers are maintained at artificially high levels through the use of supplementary feeding without considering range condition, resource degradation is assured.

Table 4 – The 30-year NPV revenue ($ * 1000) for each initial range condition to achieve maintenance of range condition (RC_{maint}), reach the maximum range condition (RC_{max}) or achieve maximum profit (NPV_{max})

Initial Range Condition	NPV_{max}		RC_{maint}		RC_{max}	
	Stocking rate (AUY 100 ha^{-1})	30-year NPV ($ * 1000)	Stocking rate (AUY 100 ha^{-1})	30-year NPV ($ * 1000)	Stocking rate (AUY 100 ha^{-1})	30-year NPV ($ * 1000)
1.25	50	1350	31	990	31	990
1.00	26	819	24	783	15	614
0.75	18	583	13	531	8	428
0.50	6	311	2	238	1	207

Table 6 – The range condition and NPV revenue consequences of stocking with 600 kg cows instead of 450 kg cows

Initial range condition	Target RC	Required SR with 450 kg cows (AUY 100 ha^{-1})	NPV ($ * 1000)	Same number of cows @ 600 kg	NPV ($ * 1000)	Final RC
1.25	1.25	31	990	40	1171	0.67
1.00	1.00	24	783	31	723	0.34
	1.25	15	614	20	712	1.19
0.75	0.75	13	531	17	569	0.41
	1.25	8	428	10	478	1.24
0.50	0.50	2	238	2.6	−1031	0.08
	1.25	1	207	1.3	223	0.08

Compounding this, large body size has become an increasingly important selection criterion in many ranching enterprises because body size is positively correlated with average daily weight gains and carcass yield (Gregory and Cundiff, 1980). It is common for livestock producers to equate greater production and animal size with increased profitability even though there is evidence that locally adapted smaller cows produce more weaned mass per cow per year than many larger breeds particularly when expressed as kg of weaned calf/100 kg cow/year (Tawonezvi et al., 1988). In addition, larger cows consume more forage, and consequently increase pressure on the range unless fewer animals are stocked to account for their larger body size. The costs of maintaining cows during periods of nutritional stress are positively related to body size; small or moderate frame cows have significantly lower maintenance costs than large cows (Van Soest, 1982; Tawonezvi et al., 1988). The effect of not adjusting for body size is illustrated in Table 6. If an area correctly stocked to maintain RC with cows weighing 450 kg is instead stocked with the same number of 600 kg cows this will result in a

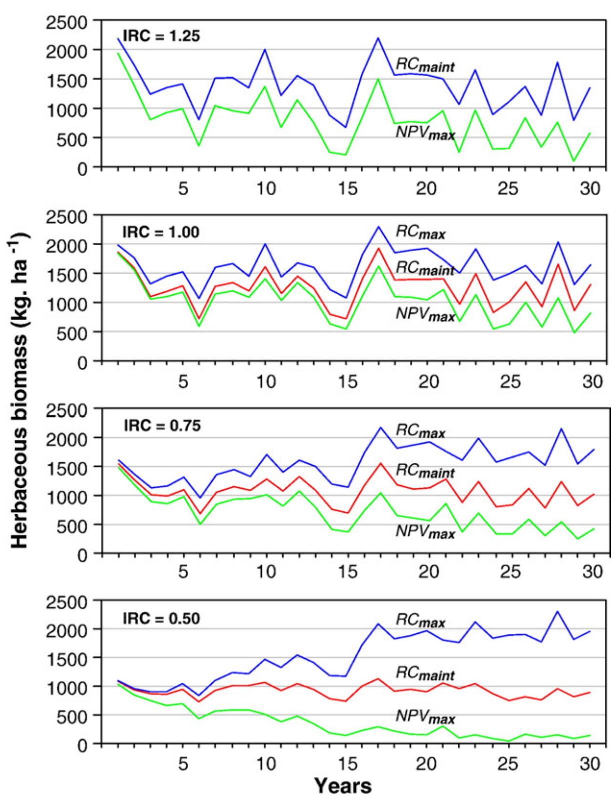

Fig. 4 – Changes in end of year herbaceous biomass (kg ha^{-1}) for each initial range condition class (IRC) at stocking rates that allow: (a) range condition (RC) to increase to the maximum RC, (b) range condition to be maintained at the initial range condition (IRC), or (c) maximum profit (NPV)($) over the simulation period of 30 years. [For IRC = 1.25 the stocking rate to maintain (Maintain RC) or reach maximum RC (Max RC) is the same].

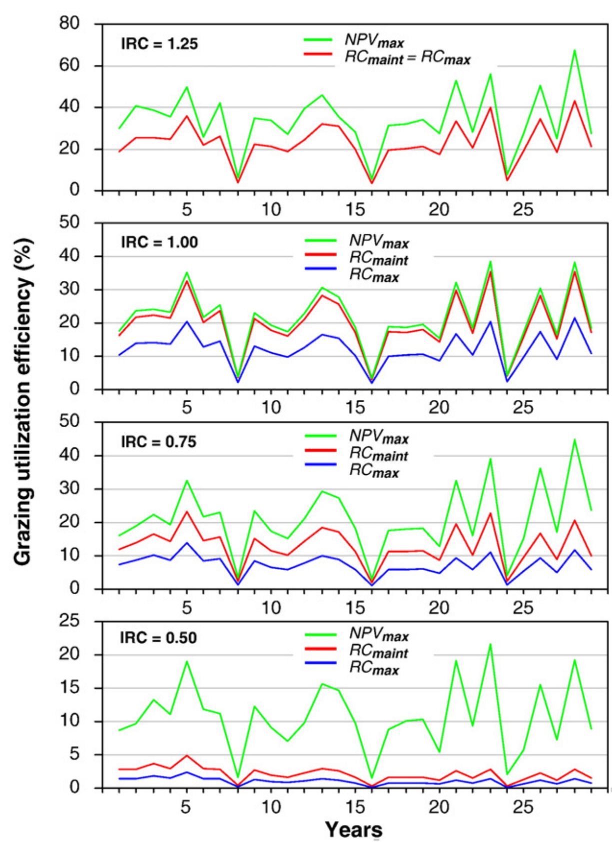

Fig. 5 – Changes in the percentage herbaceous biomass (kg ha^{-1}) consumed by livestock each year (Grazing utilization efficiency) (%) for each initial range condition class (IRC) at stocking rates that allow (a) range condition (RC) to increase to the maximum RC, (b) range condition to be maintained at the initial range condition (IRC), or (c) maximum profit (NPV) ($) over the simulation period of 30 years. [For IRC = 1.25 the stocking rate to maintain (Maintain RC) or reach maximum RC (Max RC) is the same].

Table 7 – The mean 30-year forage harvest efficiencies when managing to achieve maximum range condition (RC_{max}), maintain range condition (RC_{maint}) or achieve maximum profit (NPV_{max})

Initial range condition	Mean harvest efficiency (%)		
	NPV_{max}	RC_{maint}	RC_{max}
1.25	33	22	22
1.00	21	19	12
0.75	20	13	7
0.50	10	2	1

stocking rate that would be too high to maintain RC. Although the use of larger-bodied animals leads to higher production of weaned calf mass and profitability, this would result in a reduction in RC. Thus, range resources degrade unless they are adequately monitored and observations are translated into appropriate management actions to ensure maintenance of RC.

5.5. *Monitoring of key field parameters*

We used the model to track the simulated end-of-year herbaceous biomass (kg ha^{-1}) and percentage forage standing crop consumed each year (utilization %). These are both parameters that aid managers in selecting appropriate stocking levels to achieve their predetermined goals. The end of year biomass for each IRC and each management goal is presented in Fig. 4. As expected, the herbaceous biomass at the end of each year was highest for the goal of RC_{max}, intermediate for RC_{maint}, and lowest for NPV_{max}.

For the mid-grass prairies found in the Rolling Plains of north Texas and southern Oklahoma, White and Richardson (1991) and White and McGinty (1992) recommended 1000 kg ha^{-1} year-end forage standing crop to maintain range condition and warned that leaving less than 800 kg ha^{-1} will lead to range degradation. Simulated year-end standing crops for the RC_{maint} goal approximate 1000 kg ha^{-1} while for the RC_{max} goal they are considerably higher (1500 to 2000 kg ha^{-1}). By contrast, standing crops for the NPV_{max} goal are much lower, particularly for fair and poor IRC, and associated stocking rates lead to declining RC values.

The utilization levels associated with each IRC and management goal are presented in Fig. 5. As expected, utilization for the RC_{max} goal were lowest and those for the NPV_{max} goal were highest. For continuously grazed rangeland, the scientific community invariably advocates utilization of 20 to 25% (Heitschmidt and Taylor, 1991; Holechek et al., 2001). Model simulations for IRC = 1.25 concur with this, with predicted values ranging from 20 to 30%, with a 30-year mean of 22% (Table 7). To achieve the NPV_{max} goal, a 30-year mean utilization of 33% was predicted. For the other IRC values, much lower utilizations were predicted; the poorer the RC, the lower the utilization required. Even for the NPV_{max} goal these utilizations are extremely low at 21% for good condition and 10% for poor condition range. The values for the RC_{maint} and RC_{max} goals are even lower and those for poor condition range may indicate complete destocking of livestock, at least in a continuous grazing management system.

6. Discussion

The study reported here relates to semi-arid savanna rangelands that are continuously grazed by livestock. Using the SESS model, we use the well known observation, that level of productivity and economic returns from livestock production are positively related to range condition, to conduct quantitative analyses of the ecological and economic responses to varying stocking rates. Based on extensive field research conducted over five decades in the Rolling Plains of northern Texas and southern Oklahoma, range condition in our model is programmed to decline in response to three factors: excessive utilization (grazing pressure), the effects of below average precipitation and an increase in woody plants. By using a 50-year data base and a model from an intensively researched savanna ecosystem we were able to develop specific responses detailing the costs associated with failing to maintain range condition. We also examined the values of key field parameters that can give managers effective guidelines to avoid excessive levels of grazing that could reduce range condition.

Conservation oriented ranchers aim to optimize profitability: they try to increase profits from their rangeland-based enterprises while maintaining or improving the health of the ecosystems that produce the primary resources for their operations. This paper emphasizes the importance of choice of management goal if resources are to be managed sustainably. In order to prevent degradation of primary resources it is essential to adopt a long-term view when planning, to monitor resources through the use of meaningful and adequately sensitive parameters and to adjust animal numbers accordingly.

Workman (1986) stated that it is a fallacy to blame the profit motive for resource degradation associated with excessive stocking rates, the rationale being that diminishing economic returns and higher input costs are associated with increasing level of stocking. In the long-term, this leads to profits being maximized at lower stocking levels than those that maximize livestock production per hectare (and gross revenue), which is the goal of many producers who do not account for production costs. The underlying assumption of Workman's supposition is that the economically optimal stocking rate does not lead to decline in range condition. However, given the widely reported observation that increasing stocking rate does affect long-term range condition, this premise may be viewed as a case of maximizing short-term profit while externalizing the cost of rangeland degradation. To overcome this deficiency, a long-term livestock production function that accounts for decline in rangeland productivity with increasing stocking rate could be used to estimate the economically optimal stocking rate. However, due to the uncertainties of unpredictable climatic change effects on forage production and of herbivory on plant species composition, the derivation of long-term production functions is illusionary. This underscores the importance and utility of conducting ecological economic simulations such as this study in combination with field research.

Our results indicate that maximum profit over a 30-year period is attained at considerably higher stocking rates than are necessary for the maintenance of range condition as reported by Kothmann et al. (1970). They also show that stocking rangeland lightly in order to increase range condition will incur an opportunity cost due to reduced revenues from lower livestock production as discussed by Whitson et al. (1982). If our study had been conducted over a three to five-year period, as most field grazing studies are, there would have been no evidence of reduction in range condition in response to stocking rates that maximize profit. This underscores the danger of short-term studies, and the inescapable need to monitor suitable parameters and make timely adjustments to stocking rate if RC is to be maintained or improved. Even if stock numbers are at a level at which range condition is maintained over the long-term range condition will still vary from year to year. Our results also indicate that a relatively low stocking rate minimizes or avoids the costs and resource degradation associated with excessive grazing pressure during inevitable and unpredictable drought events. In savannas which contain woody plants that are unpalatable to grazing animals, a conservative stocking strategy is even more important if fire is used regularly to maintain invasive woody plants at low levels (Higgins et al., 2007). Low stocking is less critical where woody plants are largely palatable to browsing ungulates or where human harvesting of woody plants reduces the need to periodically suppress woody plants (Trollope, 1984).

Our results are supported by relatively long-term cow-calf stocking rate experiments on rangeland conducted in this ecoregion over 20 years. Heavily stocked treatments produced more saleable product per hectare but had greater annual fluctuations of production than moderately stocked treatments (Kothmann et al., 1971; Knight et al., 1990). For the first 10 years of the study heavy stocking produced higher net income per hectare than moderate stocking, but in the final 5 years of the study income stability was greater and supplementary feed inputs were lower on the moderately stocked treatment (Whitson et al., 1982). The primary reason for the reduced income stability was due to progressive decline in range condition represented by changes in domination from midgrasses to shortgrasses (Heitschmidt et al., 1982). Our simulations predict that the moderately stocked treatments would have been more productive and profitable than heavy stocking if these field experiments had continued for another decade.

Selection of the correct stocking rate has always been a challenge confronting rangeland managers. Stoddart and Smith (1955) classified methods for estimating grazing capacity of ranges as: (1) those in which the condition of the range is correlated with known performance at a stocking rate, and (2) those in which an estimate of carrying capacity is made based on an inventory of the forage. Inventory methods have seldom been very accurate except when carefully correlated with actual stock-carrying performance (Kothmann and Hinnant, 1999; Holechek et al., 2001). While our study indicated that maximum profit is attained at stocking rates that resulted in animal performance at 90% of maximum, this stocking rate was higher than that required to maintain range condition. At the lower stocking rate required to achieve the goal of maintaining range condition, animal performance was 93% of maximum. Since both of these points lie between the stocking rates that lead to maximum production per animal (animal performance) and maximum production per hectare, animal performance is inadequate as a monitoring parameter. On its own, the animal performance parameter is too insensitive to determine the stocking rate required to maintain or improve range condition, although it is a useful tool for assessing the approximate stocking rate that maximizes profit.

With variable climates, such as those experienced in semi-arid savannas, adequately sensitive field parameters need to be monitored so that timely adjustments can be made to animal numbers to avoid a decrease in range condition (Kothmann and Hinnant, 1999; Holechek et al., 2001). In our study, both the year-end herbaceous biomass and utilization through the year differ markedly among each of the three management goals. Consequently, they both provide a more useful and timely assessment of whether or not stocking rate needs to be adjusted, as documented in practice (White and Richardson, 1991; White and McGinty, 1992; Hanselka and Landers 1993; Ranching Systems Group, 1993; Kothmann and Hinnant, 1999).

To maintain range condition in mid-grass prairies in the Rolling Plains of north Texas and southern Oklahoma, year-end forage standing crop should approximate 1000 kg ha^{-1} (White and Richardson, 1991; White and McGinty, 1992). In our study, year-end forage standing crop for maintaining range condition varies around the 1000 kg ha^{-1} level while for the goal of returning to excellent range condition requires a considerably higher year-end standing crop of 1500 to 2000 kg ha^{-1}. Our predicted standing crop for maximizing profit is about 500 kg ha^{-1} or less after 15 years for range in fair or poor condition, and for all initial range conditions the low levels of year-end standing crop when profit is maximized lead to significant declines in range condition.

Utilization can be estimated at any time during the year by comparing the herbaceous biomass of the area being grazed with that of adjacent exclosure cages that are repositioned annually. The range science discipline advises utilization levels of 20–25% to ensure maintenance of range condition (Heitschmidt and Taylor, 1991; Holechek et al., 2001). Our results concur with this guideline for range in excellent condition (IRC = 1.25) but for range in poorer condition considerably lower utilization levels were predicted in order to maintain or improve range condition. Our model indicates that the poorer the range condition the less heavily the vegetation should be grazed to avoid range condition deterioration. There is no known field data to corroborate or refute this prediction. Since much rangeland is in only fair to poor condition, research is needed to examine this important issue. This would not have been apparent without the use of a simulation model.

7. Conclusions

Our results indicate the importance of choice of management goal if resources are to be managed sustainably. Earning capacity is four times higher for range in excellent condition than that in poor condition and maximum short-term and long-term profit is attained at higher stocking rates than would maintain long-term range condition and at much higher levels than would increase range condition levels. Stocking rangeland more lightly in order to maintain or increase range condition will incur an opportunity cost due to reduced revenues from lower livestock production but it is essential to do so to prevent degradation of the primary resource in the long-term.

Our study underscores the critical need to regularly monitor rangeland resources and to manage stocking rates of grazing herbivores in order to maintain or improve range condition. It is essential that management be based on timely monitoring of meaningful vegetation parameters and appropriate management of livestock numbers. Livestock production is not a suitable measure of stocking rates for maintaining or improving range condition. In our study, both the year-end herbaceous biomass and utilization through the year provided a more useful and timely assessment of whether and by how much stocking rate needs to be adjusted to avoid degradation of range condition.

This study deals specifically with continuously grazed rangeland. The role of rotational resting and rotational grazing as tools to decrease grazing impact and enhance recovery has been shown to have considerable potential in environments such as that studied here, in which vegetation recovery is relatively slow (Snyman, 1998; Quirk, 2002; Teague et al., 2004; Müller et al., 2007). The potential of these management options needs to be examined to compliment this study.

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Appendix A

Parameter names, symbols and units for descriptors and variables added to the model

Parameter name/symbol	Description	Units
Cactus effect on grass	Reduction of area producing grass due to cactus cover	Ha
Cactus growth	Increase in cactus cover	% of ground cover
Fine fuel	∑ Green plus dry standing crop	kg ha^{-1}
Fire intensity	Heat energy released per unit time per unit length of fire front	kJ s^{-1} m^{-1}
NPV	Net present value	$
Proportion of cactus killed	Proportional reduction in cactus cover	Proportion
Proportion of trees top killed	Proportional reduction in woody plant cover	Proportion

Appendix A (*continued*)

Parameter name/symbol	Description	Units
SC	Soil characteristics	Unit-less
Soil_CGI	Cactus growth index according to soil characteristics	Index
SR	Stocking rate	Animal unit year (AUY) 100 ha^{-1}
Tree	Aerial cover of woody plants	Woody plant cover as % of ground cover
Tree effect on grass	Reduction of grass production due to woody plants	Proportion
Tree effect on RC	Reduction in range condition due to woody plants	% reduction of range condition
Tree growth	Increase in tree cover	% of ground cover
Year	Year of simulation (i.e. 1,2, 3….30)	Years

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