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ANALYSIS

An ecological economic simulation model for assessing fire and grazing management effects on mesquite rangelands in Texas

W.R. Teague[a,c,*], W.E. Grant[b], U.P. Kreuter[c], H. Diaz-Solis[d], S. Dube[c], M.M. Kothmann[c], W.E. Pinchak[a,c], R.J. Ansley[a,c]

[a]Texas Agricultural Experiment Station, Texas A&M University System, Box 1658, Vernon, TX 76384, USA
[b]Ecological Systems Laboratory, Department of Wildlife and Fisheries Sciences, Texas A&M University, 2258 College Station, TX 77843-2258, USA
[c]Department of Ecosystem Science and Management, Texas A&M University, 2126 TAMU, College Station, TX 77843-2126, USA
[d]Departamento de Recursos Naturales Renovables, Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila 25315, Mexico

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ABSTRACT

In the southern Great Plains of North America, fire exclusion has contributed to many rangelands converting from native grassland to woody shrublands dominated by mesquite (*Prosopis glandulosa* Torr.) and cactus (*Opuntia* spp.), threatening ecosystem health and human livelihoods in the region. Prescribed fire is the least expensive method of treating mesquite and other undesirable plants, but its role is as a maintenance treatment to prolong the life of more expensive brush control treatments. Using a simulation model of a hypothetical 1000 ha ranch, we evaluate the biological and economic implications of management scenarios involving the regular application of summer fire to reduce mesquite and cactus over a 30-year time period. We compared the model output with experimental data to corroborate model output before evaluating various management scenarios over a range of stocking rates. Scenarios included (a) varying initial range condition, (b) different frequencies of summer burning, and (c) different initial amounts of mesquite brush. Model simulations corroborated field data sufficiently well to give confidence in the output of the model. In our simulations the option of not treating to reduce brush and cactus had a major negative impact on range condition, secondary productivity and profitability. In contrast, all simulated fire treatments improved range condition, productivity and profitability except when initial range condition was poor. Initial range condition and stocking rate were the major factors affecting both productivity and profitability. Compared to other factors over which managers have short-term control, frequency of burning and the initial amount of mesquite cover, had a relatively minor impact. Simulations indicated that the highest level of profit consistent with maintaining or improving range condition was attained when individual animal production was 92–95% that of the maximum production per animal, a situation invariably associated with relatively low stocking rates.

* *Corresponding author*. Texas Agricultural Experiment Station, P.O. Box 1658, Vernon, TX 76384, USA. Tel.: +1 9405529941; fax: +1 940 553 4657.
E-mail address: r-teague@tamu.edu (W.R. Teague).

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1. Introduction

North American prairies evolved under episodic grazing and widespread warm season wildfires that historically limited woody plants. However, the growth of forage-based livestock production and the threat of fire damage to buildings and structures in rural areas led to suppression of wildfires. Together with reduced grass competition from heavy livestock grazing, enhanced distribution by livestock, increased global CO_2 and removal of prairie dogs (*Cynomys ludovicianus*), fire reduction has contributed to many southern rangelands converting from native grasslands to woody shrublands (Schlesinger et al., 1990; Archer, 1994, 1995; Archer and Smeins, 1991; Collins et al., 1998; Polley et al., 1994; Kramp et al., 1998; Weltzin et al., 1998). This epidemic invasion of woody and succulent species has resulted in a decline in biodiversity (West, 1993; Knopf, 1994), a reduction in ecosystem resilience (Peterson et al., 1998), and a greater likelihood of irreversible changes in plant species composition (Westoby et al., 1989). Maintaining or restoring rangeland ecosystem health and resilience is a critical social imperative to ensure the future supply of the ecosystem services they supply, which are critical for the future well-being of human societies in the region. Such services include provision of stable soils, reliable and clean supplies of water, and the natural occurrence of plants, animals and other organisms to meet the aesthetic and cultural values and livelihoods of people living in rangelands (Grice and Hodgkinson, 2002).

Honey mesquite (*Prosopis glandulosa* Torr.) dominates many rangelands in the southern Great Plains of North America, reducing forage production and interfering with livestock foraging and management (Scifres, 1980). If left unchecked, mesquite encroachment progresses within grassland ecosystems until a closed canopy woodland thicket occurs (Ansley et al., 2004), which threatens the sustainability of livestock ranching as well as wildlife habitat (Rollins and Cearley, 2004) and grassland birds (Knopf, 1994). Increase in mesquite cover can significantly reduce grass productivity but it generally affects watersheds less than other woody species (Carlson et al., 1991). Cacti (*Opuntia* spp.) become increasingly abundant as range condition declines thereby reducing forage production and hampering livestock management (Hamilton and Ueckert, 2004).

Although it is economically rational to use aerially applied root-killing herbicides to reduce mesquite, fire is generally considered to be the least expensive method of treating mesquite and other undesirable fire-intolerant plants; yet its use as a rangeland management treatment has been mainly to prolong the life of more expensive brush control treatments (Scifres and Hamilton, 1993; Teague et al., 2001). While prescribed fire is an effective means of reducing woody plants and cacti, a threshold amount of flammable fine fuel (forage) is needed to carry fire that is sufficiently intensive to reduce woody plants (Ansley and Jacoby, 1998). Furthermore, to effectively control woody plants and cacti fire must be applied regularly (Hamilton and Ueckert, 2004). Many rangelands occur in semi-arid environments in which forage-based livestock production is the primary agricultural activity and intermittent droughts are inevitable (Thurow and Taylor, 1999). Accumulating sufficient fine fuel to carry fires in such environments requires the reduction in livestock numbers compared to areas where fire is not used. Therefore, sustainable utilization of semi-arid rangelands depends on complex management of animal species, stocking rates, and the vegetation composition, structure, phenology and quality.

While effective management requires sound ecological data about the land being managed, obtaining such data is not sufficient to ensure the implementation of restoration practices by landowners. Rational decisions at the ranch, regional and national levels, depend on researchers providing not only ecologically sound but also economically effective alternatives for land use. Furthermore, because natural resource depletion and recovery compound over time, it is necessary to assess the sustainability of management alternatives over decadal time frames (Teague, 1996). In addition, to determine the true advantage of restoration management, it is necessary to compare the benefits of changing management practices with the cost of *not* changing current practices, which rather than maintaining productivity, may lead to loss of production through shifts in plant species composition, accelerated soil erosion, and loss in biodiversity. In this paper we use the generic term “range condition” to denote overall ecosystem functional integrity and productivity.

Models have great potential as research tools to enhance our knowledge of ecosystem function and as decision aids for natural resource managers, including ranchers. They can achieve this by collating results from experiments in different fields or locations within the context of a more encompassing systems management framework that treats the ranch business as a complete bio-economic unit. In order to improve decision making, ranchers need answers to questions at the systems level, including the biological and economic elements of the rangeland production entities they are attempting to manage (Beukes et al., 2002). Simulation models can uniquely provide assessments of such bio-economic production elements at the systems level when logistics preclude local field experimentation or where assessments over decadal time frames are locally unavailable. However, to be useful as a decision aid for resource managers, models must provide predicted results that strongly correlate with field data (Teague and Foy, 2002).

In this paper we present the use of a simulation model to explore the range condition, production and economic consequences of implementing land management actions that include the use of prescribed fire applications, specifically summer fires that are more effective than cool season fires for controlling mesquite and cactus (Ansley and Jacoby, 1998; Ansley et al., 2002a; Ansley and Castellano, 2007). Based on current management practices, we assume that a method other than fire (e.g., herbicide), is used as the initial mesquite reduction treatment. Our objective was to be able to use a simple ecological economic simulation model to evaluate the bio-economic implications over a 30-year period of management scenarios that incorporate different fire frequencies, different initial amounts of mesquite, cactus, and herbaceous vegetation states (range condition) and different cattle stocking rates. We first describe how we modified the SESS model (Diaz-Solis et al., 2003) to include woody and cactus vegetation components and the ability to simulate the productivity and

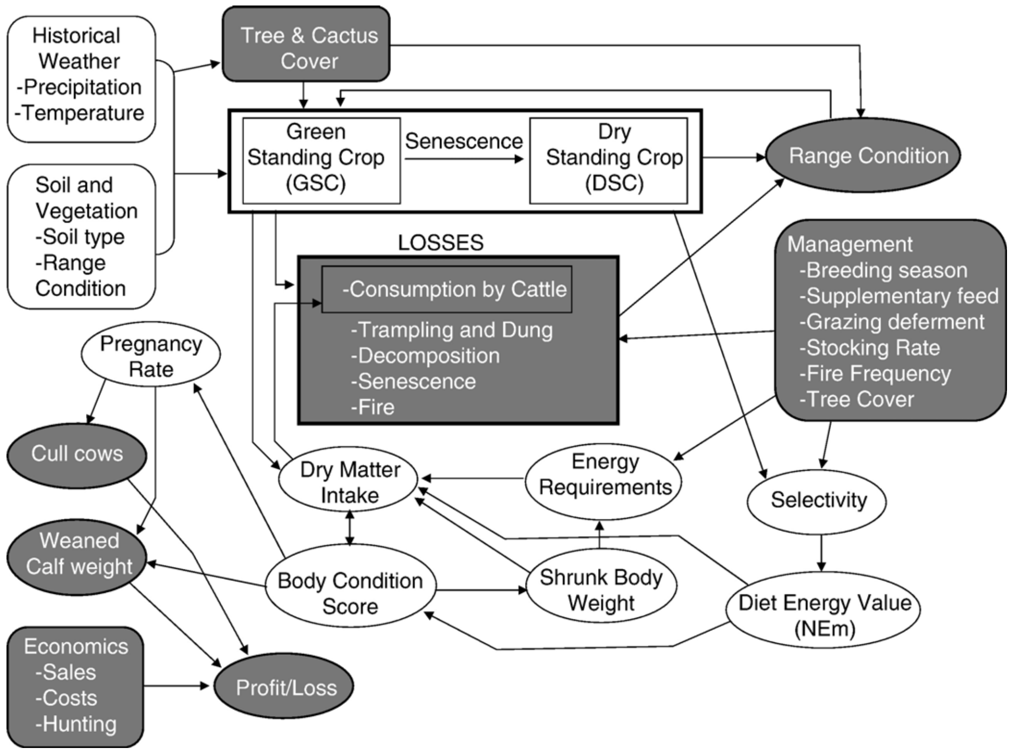

Fig. 1 – Diagram of a simple ecological economics model to assess fire and beef cattle grazing management on woody shrublands in north Texas. Shaded boxes indicate where additions or changes were made to the original SESS model of Diaz-Solis et al. (2003).

profitability of a cow-calf enterprise in north-central Texas. We then compare model output with an experimental data set to demonstrate the model's predictive reliability. Finally we present the evaluations of various management scenarios that include the application of prescribed summer fire.

2. Model description

The SESS model (Simple Ecological Sustainability Simulator) developed for north México and south Texas rangeland (Diaz-Solis et al., 2003, 2006) 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 year) simulations of semi-arid mesquite–grass rangelands in north Texas following modifications to account for climatic differences (Dube, 2005). SESS is a compartmental model based on difference equations ($\Delta t=1$ month) programmed in STELLA® 9.0 (High Performance Systems, Inc., Hanover, New Hampshire) that simulates forage production, range condition, diet selection and beef cow-calf production (Fig. 1). Parameter names, symbols and units for descriptors and variables added to the original SESS model are listed in Appendix A.

This model has been modified to simulate mesquite–grass communities in north Texas with 600–700 mm precipitation to analyze herbaceous and woody vegetation dynamics in response to grazing and burning management strategies as per the model of Glasscock et al. (2005) developed for south Texas. We use the modified SESS model to assess the long-term biological and economic implications of scenarios involving different stocking levels and strategies, fire types and frequencies, under different rainfall, soil composition, topography, and plant species composition scenarios. In conducting these simulations we use 30 years of historical mean monthly rainfall from 1970 to 2000 for Wilbarger County in north Texas. Mesquite aerial cover was used as an indicator of level of mesquite dominance. These simulations are based on herbaceous productivity and mesquite and cactus growth estimates for clay-loam soils (Ansley et al., 2004; Teague et al., in press) in the Rolling Plains region of north-central Texas (Gould, 1975).

The climate in this region is continental with an average 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 in any month. Mean monthly temperature varies from 3.9 °C in January to 36.4 °C in July.

The woody vegetation consists primarily of mesquite (*Prosopis glandulosa*) savanna up to 5 m in height and a low density of the shrub lotebush (*Ziziphus obtusifolia* (Hook. Ex. Torr. and A. Gray) A. Gray) and cactus (*Opuntia* spp). These woody species are not palatable to livestock or wildlife except for mesquite pods which are an important part of mammalian diets in late summer. The herbaceous vegetation was dominated by a cool season (C_3) perennial, Texas wintergrass (*Nassella leucotricha* Trin. and Rupr.), the warm season (C_4) perennials silver bluestem (*Bothriochloa laguroides* DC.), side-oats grama (*Bouteloua curtipendula* (Michx.) Torr.), meadow dropseed (*Sporobolus compositus* (Poir.) Merr.), buffalograss

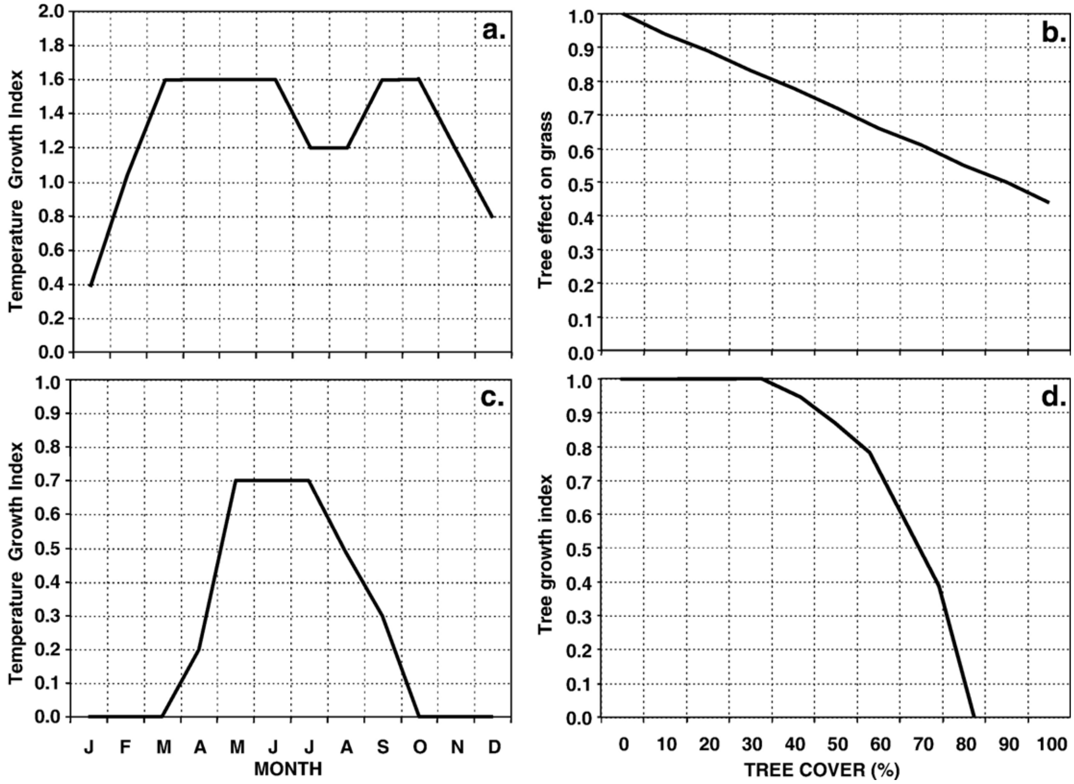

Fig. 2 – Functions used in the modified model to describe a) herbaceous growth rate modification due to mean monthly temperature, b) reduction in herbaceous production with increasing mesquite aerial cover, c) mesquite growth rate modification due to mean monthly temperature, and d) mesquite growth rate modification due to extant mesquite aerial cover.

(*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. and A. Gray) and heath aster (*Aster ericoides* L.). Nomenclature follows Diggs et al. (1999).

The primary land use on native rangeland in the area is beef cattle production, principally cow-calf systems (Teague et al., 2001). Cows are usually bred to calve in January to March and calves are weaned in October or November. Warm season grasses provide most of the herbaceous production while the significant production of cool season grasses provides significant green grass through winter to lower winter feed costs for livestock (Teague et al., 2001). Income from wildlife based enterprises is increasingly important (Bernardo et al., 1994).

2.1. *Forage growth*

Since the original SESS model was parameterized for north Mexico and southern Texas, the forage submodel was modified to generate herbaceous growth in North Texas. Modifications accounted for differences in soil type (clay-loam of Tilman series in Wilbarger County (NRCS, 2006)), temperature (Fig. 2a) and measured mesquite aerial cover and cactus cover in the region (Teague et al., in press). The temperatures in July and August are high enough to limit the amount of herbaceous growth in these months regardless of the amount of rainfall that is expected in these months. Hence the low growth indices for these months in Fig. 2a. Herbaceous production declines with increasing mesquite cover through competition for resources, and this influence is included in the model using data collected in this region (Fig. 2b) (Ansley et al., 2004; Teague et al., in press).

2.2. *Tree and cactus growth and competition with forage*

Mesquite growth estimates (aerial tree percent cover) were based on growth rates measured in the region (Teague et al., in press) and were modified in the model for soil type, temperature (Fig. 2c) and extant mesquite aerial cover (Fig. 2d). The model allows specification of the starting value of tree cover.

Cactus growth was similarly estimated from measured annual increases in percent aerial cover on clay loam soils in the region (Teague, unpublished data). Growth per month is calculated as:

$$\text{Cactus growth} = \text{Soil\_CGI}^{*}0.042 \qquad (1)$$

where Soil_CGI is a cactus growth index based on soil characteristics (Appendix A). An index of 1 was ascribed to the soil being simulated and field data collected on this soil were used to calculate this function. Cactus does not have the same competitive exclusionary effect on herbaceous production as mesquite but it does physically exclude herbaceous plants from growing in the same area. The model simulates the effect of cactus on herbaceous production by subtracting the area occupied by cactus from the area available for herbaceous plants. The starting value for cactus cover is determined in the model from the specified initial range condition. Specifically, initial cactus cover values are 0, 5, 10 and 15% for Excellent, Good, Fair, and Poor range condition classes, respectively. These values were determined from field data collected in the region.

2.3. Range condition

The range condition (productivity, health and composition) submodel represents long-term changes in range productivity based on the proportion of annual net primary herbaceous production (ANPP) consumed by cattle, or Utilization Efficiency (UE). Range Condition class (RC) is quantified on a relative scale to represent ranges in Excellent (RC=1.25), Good (RC=1.0), Fair (RC=0.75), and Poor (RC=0.50) classes as in the original SESS model (Diaz-Solis et al., 2003). The diet selection submodel estimates the proportions of green and dry forage in cattle diets based on preference and harvestibility. Changes in RC are calculated for rainfall of 700 mm from UE as in the original SESS model. For details see Diaz-Solis et al. (2003).

As outlined above, 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 each month in the model to represent the effect of mesquite expansion on herbaceous composition and forage productivity (Ansley et al., 2004; Teague et al., in press). Quantitatively this is expressed by the following function:

$$\text{Tree effect on RC} = 0.00175 - 0.000006^{*}\text{Tree} \tag{2}$$

Range condition does not decline as a result of grazing pressure only. Drought can also result in herbaceous changes that lower productive potential (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} based on perennial grass basal cover declines 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.

2.4. Fire intensity and tree and cactus mortality

The submodel for simulating fire intensity was derived from the model developed for savanna communities by Trollope (1999) using the rate of spread model developed by Albini (1976), which was, in turn, based on the Rothermal (1972) fire behavior model. In addition, the fire intensity submodel assumes relative humidity of 30%, wind speed of 45 m s^{-1} (16 km h^{-1}) and fuel moisture of 20%, which are based on average field conditions under which experimental summer burns were conducted in the Rolling Plains by Ansley and Jacoby (1998).

$$\text{Fire Intensity} = 340 + (\text{Fine fuel}^{*}\,0.0868) \tag{3}$$

The proportion of mesquite trees top killed following each fire is calculated as a function of fire intensity using summer burn data from this location reported by Ansley and Jacoby (1998).

$$\text{Proportion of trees top killed} = (\ln(\text{Fire Intensity})^{*}25.72) - 121 \tag{4}$$

These functions calculate mesquite top kills of 62%, 75% and 84% at Fine Fuel amounts of 1000, 2000 and 3000 kg ha^{-1}, respectively using the average field conditions under which summer fires are conducted in this area. The tree sizes in the experiments reported by Ansley and Jacoby (1998) ranged from seedlings, regrowth and mature trees up to approximately 5 m in height commonly found in this region.

Since there was no quantitative data for cactus kill with different fire intensities, we assumed the same function as above based on the work of Bunting et al. (1980) and Ansley and Castellano (2007) who report >85% cactus mortality 3 years after prescribed summer fire in this environment:

$$\text{Proportion cactus killed} = (\ln(\text{Fire Intensity})^{*}25.72) - 121 \tag{5}$$

2.5. Deferral of grazing

Recently burned areas are preferred to unburned areas and Wright (1974) advised that access of grazing animals to burned areas should be restricted to prevent overuse of these areas. In addition, when burning to reduce brush, deferral of grazing prior to burning results in higher and more continuous fuel loads, more uniform and intense fires and more effective brush kill (Ansley et al., 2005). Therefore, the model simulates deferment of grazing prior to and after each burn by excluding grazing from the area to be burned in August for a full calendar year. Grazing is spread evenly over the non-deferred portion.

2.6. Cattle production model

The diet selection, intake rates and animal performance in this model are unchanged from the original SESS model (Diaz-Solis et al., 2003). Stocking rates are expressed in AUY 100 ha^{-1}, where AUY (animal unit year) is an animal unit (450 kg cow) grazing for 365 days.

2.7. Economics

An economic submodel was added to the original SESS model to calculate annual profit or loss and to determine Net Present Value (NPV) of alternative rangeland management options being considered. NPV was calculated as follows (Workman, 1986):

$$\text{NPV} = \text{Profit}/(1+r)^{n} \tag{6}$$

where r is the selected discount rate for future benefits and costs and n is the year within a 30-year planning horizon. The value for the discount rate was set at 5% per year based on discussion by Workman (1986). Values for n range increment in yearly time steps from 1 through 30. The total net values (TNV) for each 30-year simulation period is used to compare the economic values of alternative treatments. Annual revenues and costs for a standard cow-calf operation and a hunting enterprise are calculated as:

$$\text{Revenue} = (\text{Weaner income}) + (\text{Cull cow income}) + (\text{Hunting income}) \tag{7}$$

$$\text{Costs} = (\text{Cow production costs}) + (\text{Cow cost}) + (\text{Brush control cost}) \tag{8}$$

We used the average prices and costs (2000 to 2005) for leased cow-calf ranchland in the Rolling Plains of Texas

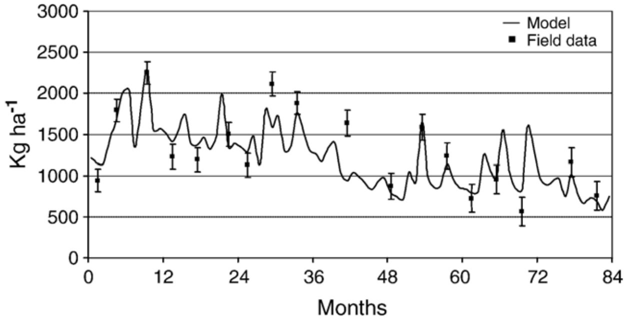

Fig. 3 – Model output compared to field data for grass standing crop biomass (fine fuel) (Mean ± SE, *n* = 8).

(Bevers pers. Comm.[1]) for total annual cost per cow ($350), replacement cow costs ($750 per cow), sales prices for weaner calves ($2.10 per kg live weight) and cull cows ($500 per cow), and hunting lease revenue ($ 12 per ha). Cost of treating brush includes only the costs of prescribed burning ($4.70 ha^{-1}; Bevers pers. Comm.). This includes the costs of preparing fire safety lines before burning and the costs of applying the burns for pastures ranging in size from 120 ha to 250 ha. There is no cost of grazing deferment since the cattle are spread evenly over all pastures that will not be burned that year, as indicated above.

3. Model evaluation

Output from the model was evaluated by comparing it to data collected in a grazing experiment involving 8 ranch-sized management units varying from 1283 to 2130 ha conducted in mesquite grass communities representative of the Rolling Plains ecoregion in Wilbarger County, Texas (Teague et al., 2004; Ansley et al., 2005). Exact comparisons could not be made because each experimental management unit was comprised of 3 major range sites while the model simulates only one of these sites, clay-loam soils of the Tilman series, which made up approximately 60% of each experimental unit. Herbaceous standing crop (fine fuel) was measured for each soil series for direct comparison with the model output. However, the animal production data output from the model will differ from that of the field data since 30% of the experimental area consisted of shallow clay soils that produced approximately 70% the herbaceous biomass produced on the clay-loam soils (NRCS, 2006; Teague et al., in press).

Model evaluation found that forage standing crop is simulated reasonably well with the simulated means falling within one standard error for 12 of the 18 field data points (Fig. 3). The simulated mean for the entire period was within one standard error of that measured (i.e. 1242 kg ha^{-1} vs. 1323 ± 155 kg ha^{-1}, respectively). Pregnancy percentage of cows, one of the most important criteria influencing ranch profitability, was in all simulations close to the observed values each year (Table 1). The mean calf mass each year was more variable but the simulated mean for the entire period was only slightly less than that measured (i.e. 230 kg calf^{-1} vs. 233 kg calf^{-1} ± 4.5, respectively). Therefore, based on the model evaluation, the predicted simulation values are considered to be sufficiently close to measured data.

[1] Stan Bevers, Extension Economist, Texas Cooperative Extension, P.O. Box 1658, Vernon, Texas 76385.

4. Scenario analyses

On rangelands, managers have a restricted number of actions under their direct control to achieve production, conservation and profitability goals. In the short-term they can control stocking rate, which directly influences the amount of fine fuel available for carrying fire as well as animal production. They can also decide on the frequency and time of year to burn. If mesquite brush levels are considered to be too high for fire to be effective, managers can use other tools such as spraying of herbicides to reduce brush and subsequently decide when and at what level of brush cover to burn to manage brush levels.

We analyzed several scenarios to determine the range condition, production and profitability consequences of using fire to reduce brush and cactus. We compared each of these scenarios with the option of not burning. The analyses were conducted using a range of realistic stocking rates. The lowest stocking rate used in the simulations, 5 AUY 100 ha^{-1}, was chosen to determine highest possible individual animal production values. Scenarios included varying the following:

a) Initial range condition (IRC)
b) Different frequencies of summer burning, and
c) Initial amounts of mesquite brush.

4.1. *Initial range condition*

The model showed a high degree of sensitivity to changes in IRC. The mean fine fuel amounts for the 30-year simulations declined with decreasing IRC's and steadily declined within each IRC as stocking rate increased (Fig. 4a). The fine fuel biomass of the burn treatment exceeded that of the no-burn treatment at all but the highest stocking rates by a large margin except at the lowest IRC (0.5). Burning range in poor

Table 1 – Model output for pregnancy percentage and mean calf mass compared to field data (Means ± SE, *n* = 8)

Year	Parameter			
	Pregnancy[a] (%)		Calf mass[a] (kg calf^{-1})	
	Data	Model	Data	Model
1995	90 ± 3.4	89	226 ± 4.5	215
1996	80 ± 3.4	90	188 ± 4.5	227
1997	89 ± 3.4	90	244 ± 4.5	233
1998	87 ± 3.4	88	223 ± 4.5	243
1999	89 ± 3.4	92	254 ± 4.5	279
2000	84 ± 3.4	89	260 ± 4.5	221
2001	86 ± 3.4	87	235 ± 4.5	189
Mean	86 ± 3.4	89	233 ± 4.5	230

[a] At weaning in late October.

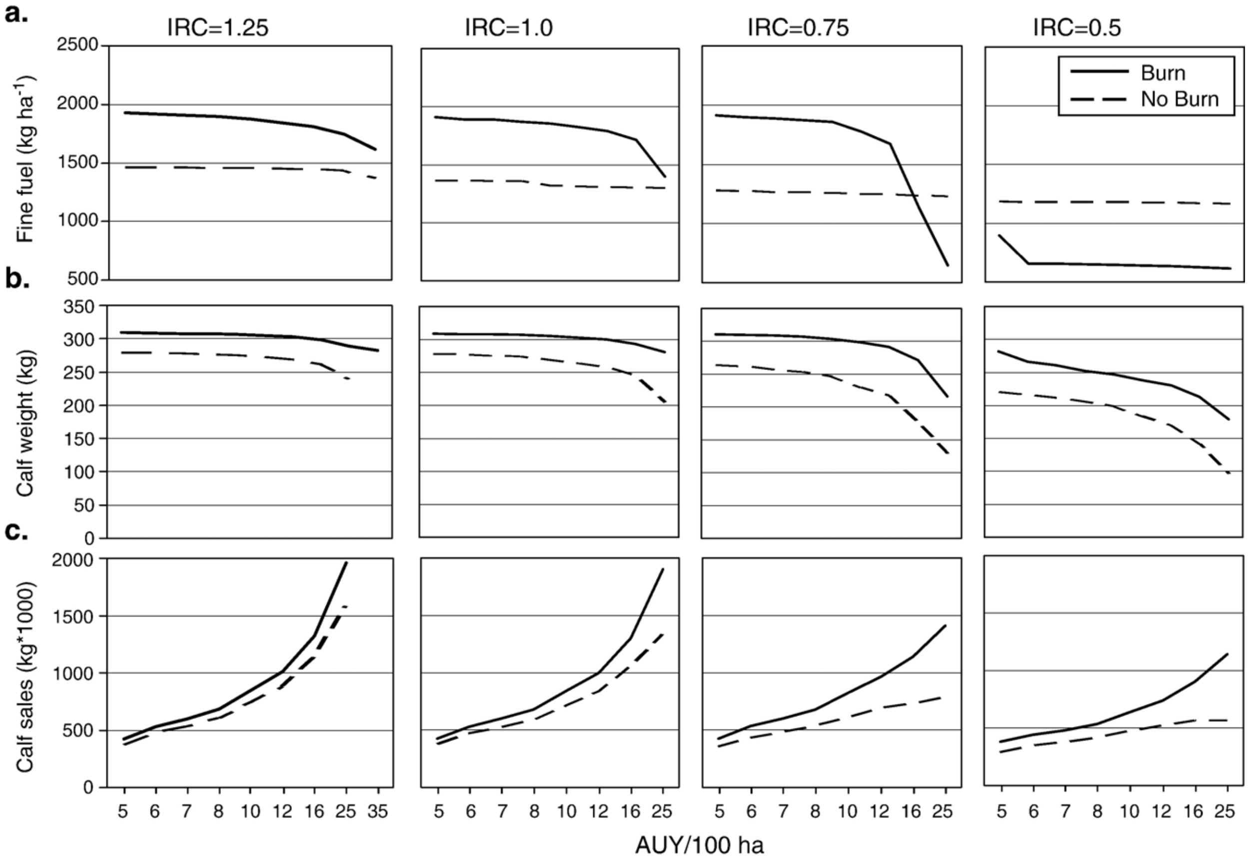

Fig. 4 – Simulated 30-year system response with different initial range condition (IRC's) for not burning and burning at a fire frequency of 6 years for (a) mean fine fuel amounts (kg ha^{-1}), (b) mean calf weight at weaning (kg), and (c) total weight of calves sold (kg).

condition caused the simulated herbaceous vegetation to crash to low biomass levels at even the lowest stocking rates. As discussed above, the model decreases range condition (RC) each year if herbaceous biomass is less than 800 kg ha^{-1} at the end of summer. Burning of range in poor condition (RC=0.5) results in this happening even at the lowest stocking rates

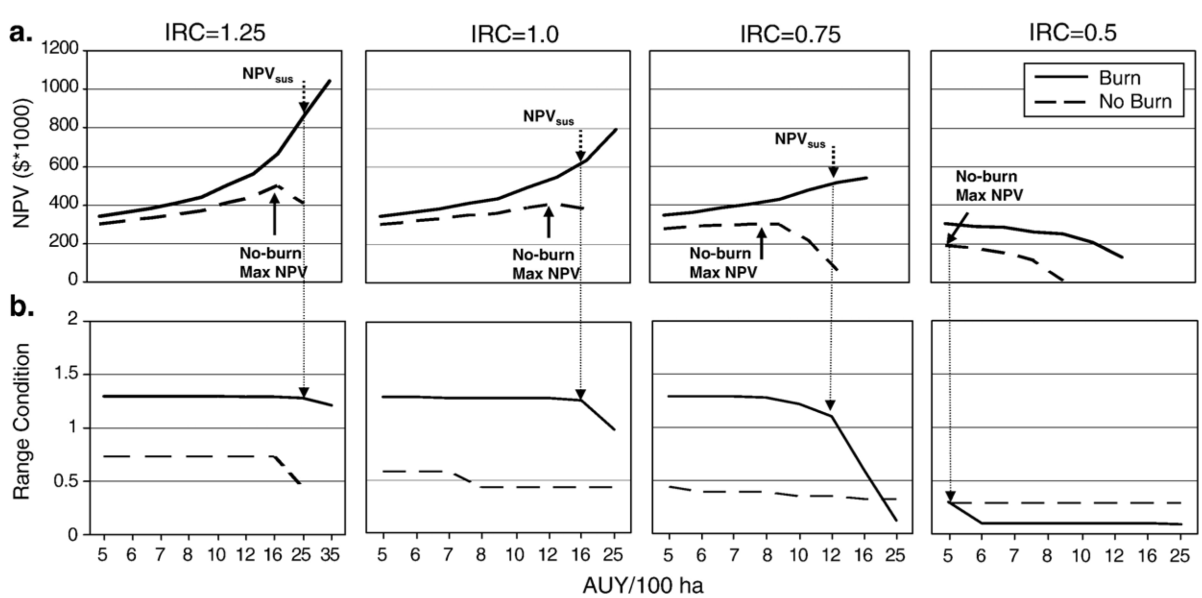

Fig. 5 – Simulated 30-year system response with different initial range condition (IRC's) for not burning and burning at a fire frequency of 6 years for (a) economic profit (NPV), and (b) range condition changes. The arrows indicate the stocking rate at the values of highest sustainable NPV (NPV_{sus}).

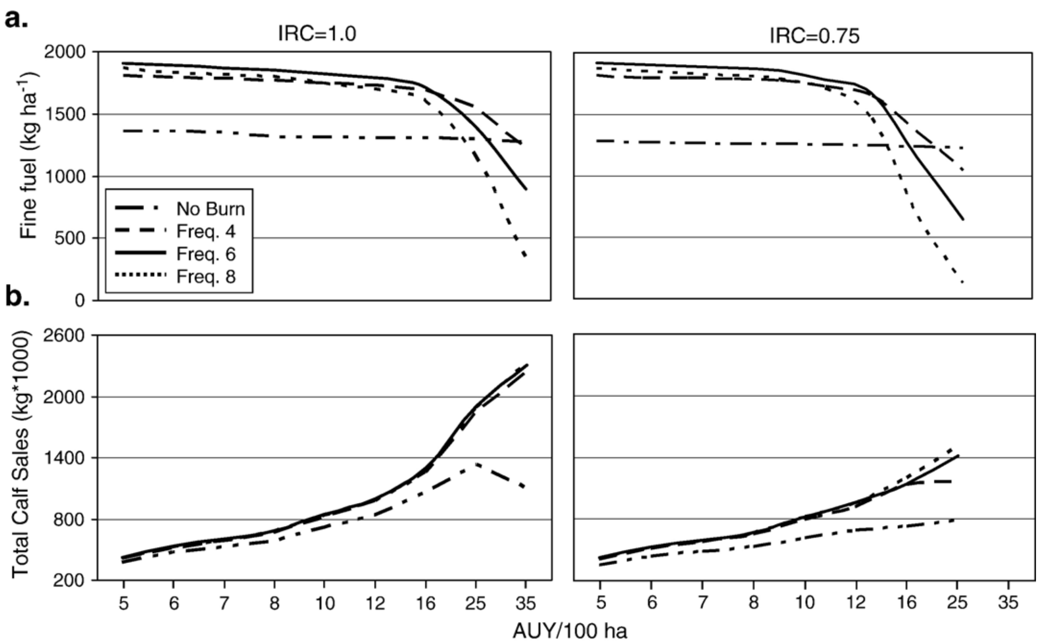

Fig. 6 – Simulated 30-year system response to different fire frequencies with initial range conditions of 1 and 0.75 for (a) Mean fine fuel amounts (kg ha^{-1}), and (b) total weight of calves sold (kg).

simulated. This is due to the very low primary productivity of poor condition range not being able to sustain even low levels of grazing in the simulated management unit.

Individual calf weights at weaning (Fig. 4b) and total sale of weaned calves (Fig. 4c) both reflect these differences in forage biomass. Similarly, all burning treatments recorded higher forage and calf productivity than not burning at all stocking rates.

NPV's for the 30-year simulations showed large differences between the burn treatments and not burning for each IRC (Fig. 5a). With no burning the increase in mesquite brush results in an annual decline in RC (Fig. 5b). The highest sustainable NPV's (NPV_{sus}) are assumed to occur at stocking rates that maintain or increase RC over the 30-year simulation (cf. Fig. 5a and b). For each IRC the NPV_{sus} was higher for the burn treatment than for not burning (cf. Fig. 5a and b). Furthermore, the

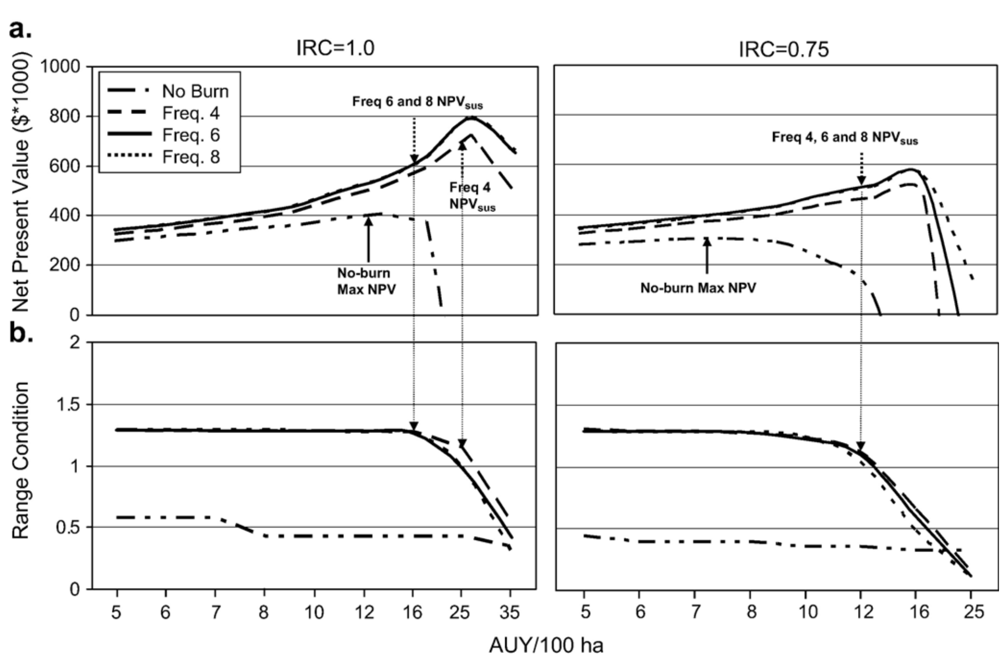

Fig. 7 – Simulated 30-year system response to different fire frequencies with initial range conditions of 1 and 0.75 for (a) economic profit (NPV), and (b) range condition changes. The arrows indicate the stocking rate at the values of highest sustainable NPV (NPV_{sus}).

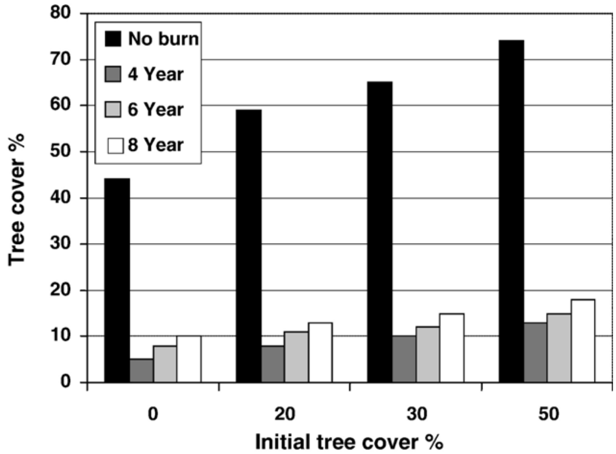

Fig. 8 – Simulated 30-year mean tree cover with different initial tree cover values and an initial range condition of 1 with no-burning and burn frequencies of 4, 6 and 8 years.

maximum NPV's for the no-burns were not sustainable since the presence of increasing brush decreases range condition.

It is also interesting that for all IRC values the calf weaning weights at the highest sustainable NPV's were 92–96% that of the maximum weaning weight achieved at the lowest stocking rates. This indicates that to maintain the highest levels of sustainable profit, stocking rates should be low enough to give only slightly less individual animal performance than the maximum possible.

4.2. *Fire frequency*

The effect of fire frequency is simulated at IRC values of 1 and 0.75 as these are the two range conditions most likely to be encountered on ranches where burning would be considered as a brush reduction treatment. A frequency greater than 8 years between burns was not included in this analysis because in our simulations fire frequencies greater than 8 years did not result in higher productivity and sustainable profitability. In addition, field data indicates that pretreatment mesquite cover levels are reached in 6 to 8 years after treatment (Teague et al., 2003).

Burning at intervals of 4, 6 and 8 years all resulted in higher productivity (Fig. 6a and b) and profitability (Fig. 7a) than not burning. Range condition with not burning was consistently lower than for the burn treatments (Fig. 7b) because of the negative effects of mesquite on herbaceous production and changes in species composition outlined in Section 2.3 above.

Regarding the superiority of the different frequencies of burning, there was an interaction with IRC. At an IRC of 0.75 the fine fuel biomass, total weight of weaned calves and sustainable NPV's were highest with a burn frequency of 6 years followed by the 8-year frequency treatment, and all three of the burning frequency treatments had the highest NPV_{sus} values at a stocking rate of about 12 AUY 100 ha^{-1} (Fig. 7a). All burning frequencies resulted in 30-year mean mesquite cover of 10% or less.

With an IRC of 1 or higher the highest NPV_{sus} was at a burn frequency of 4 years at a stocking rate of 25 AUY 100 ha^{-1} (Fig. 7a), while the highest NPV_{sus} at 6 and 8-year burning frequencies were both at a stocking rate of 16 AUY 100 ha^{-1}. Although the 6-year and 8-year burn frequencies showed higher fine fuel and total weight weaned than the 4-year burn at lower stocking rates, this was reversed at higher stocking rates. This resulted in the overall highest NPV_{sus} occurring when the 4-year burn rotation was applied and stocking rates were 25 AUY 100 ha^{-1}. This result is explained by the fact that range condition at the higher stocking rate was affected less by burning at a frequency of 4 years (Fig. 7b). This was largely due

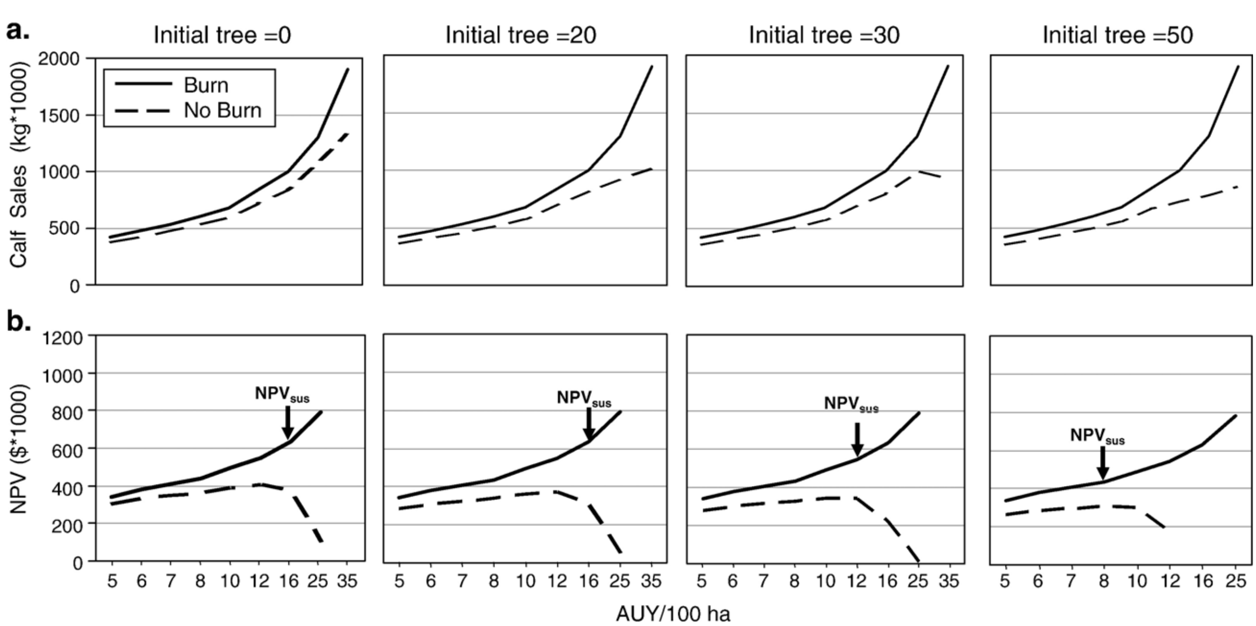

Fig. 9 – Simulated 30-year system response to not burning compared with burning at a frequency of 6 years for an initial range condition of 1 with different initial amounts of tree cover for (a) total weight of calves sold and (b) economic profit (NPV). The arrows indicate the stocking rate at the highest sustainable NPV values (NPV_{sus}).

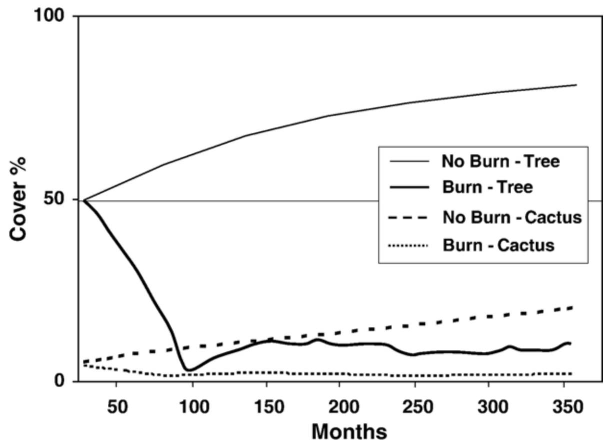

Fig. 10 – Simulated 30-year mesquite and cactus cover values with initial mesquite cover of 50%, an initial range condition of 0.75 for not burning and a burn frequency of 6 years.

to mesquite brush aerial cover being maintained at a mean of 5% for the 4-year burns compared to 8% for the 6-year and 10% for the 8-year year burns, which resulted in slightly higher forage (fine fuel) amounts for the 4-year burn frequency at the higher stocking rates (Fig. 6a).

With no burning, the maximum profit (NPV) for IRC's of 1 and 0.75 were at stocking rates of 12 AUY 100 ha^{-1} and 7 AUY 100 ha^{-1}, respectively (Fig. 10a). However, since the presence of mesquite and cactus decreases range condition, not reducing mesquite and cactus cannot be considered sustainable in terms of species composition, productivity, ecosystem function or profitability.

4.3. *Initial tree cover*

The amount of mesquite cover was considerably greater with no-burning than for all frequencies of burning, but there were only small differences in mesquite cover between 4, 6 and 8-year burning intervals (Fig. 8). As a consequence, although initial mesquite cover significantly reduced both productivity and profitability when fire was excluded, the presence of small amounts of mesquite under any of the different burning treatments had little effect (Fig. 9a and b). This is applicable only if IRC is 0.75 or higher because, when IRC is poor (IRC=0.5) insufficient fine fuel is produced for fire to be an effective brush reduction treatment and instead burning causes herbaceous productivity to crash (Fig. 5b). Our simulations also showed that for IRC values of 1 or 1.25, NPV declined by only 1% when initial mesquite cover increased from 0% to 50%, while when IRC was 0.75 NPV declined by 9% for the same increase in mesquite cover.

The relatively minor response to differences in initial mesquite cover is primarily due to two factors. First, mesquite suppresses herbaceous growth only moderately and even at a mesquite cover of 50% fine fuel production is still 70% of maximum. Second, burning in summer commonly results in high intensity fires because fuel at this time is usually dry and relative humidity is usually low (25 to 30%). As a result, a fine fuel loads as low as 1000 kg ha^{-1} will result in fires that are intense enough to top kill 62% of mesquite plants under the climatic conditions that prevail in late summer. With the simulation burn treatments both the mesquite and cactus cover are reduced to low levels in less than 100 months (Fig. 10).

4.4. *Field data evaluation of optimal stocking rate simulation*

For the clay-loam range site in our field experiment the mean maximum herbaceous standing crop at the end of summer between 1995 and 2001 was 1746 kg ha^{-1} (Teague et al., in press). Over the same time period, range condition based on species composition and Natural Resources Conservation Service standards was estimated to be fair to good (NRCS, 2006). Further, mean mesquite cover on this range site during the same period was 31%, which, when using Fig. 3, results in a mean maximum standing crop of 2104 kg ha^{-1}. The NRCS base correct stocking rate guidelines on 25% of peak standing crop per cow for 365 days. Using this method, our field data for the six-year period 1995 through 2001 indicates a correct stocking rate of 11 cows 100 ha^{-1}. This compares favorably with the model prediction of 12 cows 100 ha^{-1} for range in fair condition (RC=0.75) for all three simulated burning frequencies (Fig. 5a). As indicated above, this coincided with animal productivity of 92–96% of maximum production per animal.

5. Discussion

The fundamental purpose of our model was to determine how to best manage rangelands using summer fire to reduce mesquite and cactus while maximizing profitability without diminishing the long term condition of the rangeland ecosystem. Model output agrees sufficiently well with field measurements to give confidence in the model simulations. In these simulations not burning resulted in moderate levels of productivity and lower rangeland management costs in the short-term (10 years or less), but eventually the increase in mesquite and cactus reduced range condition, productivity and profitability. Over the 30-year simulation period, the stocking rates that maximized profitability (NPV) when fire was not applied were much lower than those producing the highest sustainable profits when burn treatments were incorporated.

We found that initial range condition and stocking rate were the major factors affecting both productivity and profitability in the short-term, while other factors that managers can control, including frequency of burning and the initial amount of mesquite cover, had a relatively minor impact. The effect of stocking rate is doubly important because, in addition to affecting the amount of forage available to livestock, it also governs the amount of fine fuel and hence fire intensity and the reduction in the amount of mesquite. Therefore, in the long term, stocking rate is considered to be the prime factor governing the rangeland health (range condition), which in turn determines ecosystem function and productivity as well as ranch profitability (Holechek et al., 2001). To sustain rangeland resources and not adversely affect profitability, stocking rates should lie within the range between maximum production per animal and maximum production per hectare (Riechers et al., 1989; Hatch et al., 1996). Our model indicated that the highest level of profit consistent with maintaining or improving range condition was attained when individual animal performance was 92–96% that of the maximum potential animal performance, which invariably occurs at relatively low stocking rates (Heitschmidt and Taylor, 1991; Holechek et al., 2001). A conservative stocking rate is even more important in areas with a very variable climate if fire is to be used as a tool because regular burning is required for fire to be effective (Hamilton and Ueckert, 2004). In times of below average rainfall, applying fire can be difficult or impossible due to inadequate fine fuel loads. Under such conditions, reducing stock numbers and annually burning only 10–12% of the grazing management unit is necessary to ensure regular burns that suppress brush and maintain herbaceous plants and thus high long-term profitability (Scifres and Hamilton, 1993; Teague et al., 2001).

Several authors (Behnke and Scoones, 1993; Shackleton, 1993; Tapson, 1993; Scoones, 1995) maintain that increasing stocking rates so that production per animal is reduced would not lead to degradation of the range in areas semi-arid rangeland with variable rainfall. This appears to be the case in environments where some factor or combination of factors results in maintenance of productive herbaceous vegetation. Such conditions do occur on communal grazing areas in southern Africa where animal numbers are very low after droughts due to drought related mortality, edaphic conditions allow the herbaceous layer to effectively compete with woody plants. In addition, in the areas referred to by these authors, woody plants are often palatable to browsers which are suppressed by wild or domestic browsing ungulates, such as goats, and there is considerable harvesting of woody plants by the human population (Teague and Smit, 1992). However, in the environment of this study, where the unpalatable woody dominant mesquite fairly quickly suppresses herbaceous production and changes herbaceous species composition, primary and secondary productivity decline significantly unless there is a regular decrease in mesquite by means such as prescribed fire. In the absence of fire, chemical or mechanical means can be used but this option is considerably less profitable due to the higher costs of treatment (Teague et al., 2001). Under the conditions found in the study area region, prolonged heavy stocking rates negatively effect herbaceous productivity and composition and quickly eliminate the option of using prescribed fire to cheaply maintain low levels of mesquite.

Regarding different strategies of using fire to be effective in reducing brush, a threshold amount of flammable fine fuel must be provided regularly, even in times of below average rainfall (Wright and Bailey, 1982). The more frequently the prescribed fire is applied, the higher will be the total cost, but if fire is applied too infrequently brush will be too abundant and fine fuel loads will be inadequate for fire treatments to be effective, which will necessitate the use of more expensive chemical or mechanical treatments to reduce brush (Teague et al., 2001). At the correct stocking rate, the frequency of fire must be decided in order to maintain brush below a threshold above which fire efficacy be would reduced. Our model predicts fairly similar "optimal" stocking rates that allow effective brush control when burning at 4, 6 or 8-year intervals. By comparison, field data indicate an optimal stocking rate when using fire of 11 AUY 100 ha^{-1} with an average mesquite cover of 31%. This corroborates the output from our model, i.e. a stocking rate of approximately 12 AUY 100 ha^{-1} for the highest NPV is consistent with improving or maintaining range condition.

At the correct stocking rate, the strategic choice is whether to burn frequently to keep brush levels low or not burning until just before fire would become ineffective. By using actual weather data for a 30-year period in these simulations the vagaries of the weather were taken into account. The simulations suggest that when range condition is excellent or good, a frequency of 4 to 6 years would be optimal while a frequency of 6 to 8 years would be optimal when vegetation is in only fair condition. Simulations also suggest that a burning interval of greater than 8 years would be detrimental to long-term range condition and profitability. This is consistent with field data that indicated mesquite levels return to pretreatment levels in 7 to 8 years following fire (Teague et al., 2003).

In these summer burning simulations it is significant that the highest sustainable NPV values for all fire treatments occurred with 30-year mean mesquite cover levels of 10% or less. This is consistent with an analysis of winter burning effects on mesquite, which found an economic advantage for using fire when the canopy cover of mesquite reached 10–15% after the application of root-killing herbicide (Teague et al., 2003). Delaying the application of fire until after mesquite densities exceeded this threshold resulted in a sharp escalation of the costs of restoring the productive capacity of rangelands. In addition, ecological thresholds of mesquite density may be reached beyond which it may be impossible to economically restore a rangeland plant community that is suitable for livestock or wildlife production.

Although the purpose of applying prescribed fire in many rangeland ecosystems is to prolong the effective life of more expensive initial brush control treatments (Hamilton and Ueckert, 2004), it is economically rational to use fire to reduce mesquite whenever possible and to limit the use of more expensive chemical or mechanical treatments to periods when the application of fire is not feasible (Teague et al., 2001). In our simulation study there was a lack of sensitivity to initial mesquite levels. This is probably a function of the superior efficacy of summer vs. winter fire in controlling mesquite and cactus (Ansley and Jacoby, 1998; Ansley et al., 2002a; Ansley and Castellano, 2007). As mesquite density exceeds 25% cover in our study area, grasses that grow during the winter and with which mesquite compete less directly become more abundant than summer grasses (Ansley et al., 2004; Teague et al., in press). Further, since winter rainfall is significant in this region, winter fire is less effective than summer fire because the moisture content of fuel is higher and its flammability lower than that of the same fine fuel loads in the summer.

In our simulations of summer burning there was sufficient fine fuel to ensure effective mesquite top-killing burns except when stocking rate was excessive. In our study area, late summer burns are usually conducted under field conditions that result in mesquite top kills of 60% or better with at least 1000 kg ha^{-1} of fine fuel. This contrasts with a previous study simulating winter burning (Teague et al., 2003) in which the efficacy of the brush reduction fires was reduced above 15–20% mesquite cover, due in large part to the increase in presence of wintergrass at the higher levels of mesquite cover.

In summary, our model simulations showed that in Rolling Plains rangelands that are in fair to excellent condition the application of summer fires every 4 to 8 years is effective in initially top killing mesquite and cacti and subsequently maintaining them at levels that enhance rangeland productivity and ranch profitability. This result has been corroborated by field research in the region and is consistent with the observed preference of some ranchers to use summer rather than winter fires to reduce mesquite and cactus even though winter fires are less hazardous. The suppression of fire in general and summer fire in particular has been driven largely by the perception of livestock producers that applying fire to rangelands "wastes" forage. In reality, fire suppression along with overgrazing has led to the widespread conversion of open grasslands and savannas to increasingly thicketized shrublands and closed canopy woodlands (Schlesinger et al., 1990; Archer and Smeins, 1991; Archer, 1994, 1995; Collins et al., 1998), which has led to a decline in productivity of these rangelands for livestock production and even wildlife.

Today, despite historical evidence to the contrary, resistance to prescribed summer fire is driven by concerns over the potential damage to ecosystems and about legal liability for damages associated with the loss of control of such fires. Yet, the increase in above ground woody plant biomass combined with increasing global temperatures appears to be resulting in increasingly frequent catastrophic wildfires that are costly and much more difficult to control. Another concern is that the application of fire will increase the release of carbon dioxide, thereby exacerbating global warming. However, compared to unburned areas, soil carbon and nitrogen in the study area were found to increase following summer fire, offsetting initial carbon losses from combustion within 28 days in a wet year and 82 days in a dry year (Ansley et al., 2002b, 2006). Therefore, in both wet and dry years it is likely that the amount of carbon emitted during a prescribed summer burn is taken up by regrowing herbaceous plants by the end of the first growing season following fire. Based on our model simulations and other researchers' field research results in our study area, there is, therefore, little evidence to justify resistance to the use of prescribed summer fire as a rangeland restoration and management tool. Research is currently being conducted to rigorously evaluate the ecological, economic and social implications of the use of prescribed summer fire as a rangeland restoration tool in three eco-regions within the Southern Plains, including the Rolling Plains.

6. Conclusions

Most conservation oriented ranchers attempt to maximize profitability while maintaining or improving the health of the ecosystems that provide the resources necessary for their operations. Ensuring the future supply of ecosystem services by maintaining or restoring ecosystem health and resilience is critical for the future well-being of human societies in the region. The relentless invasion of woody plants, such as mesquite, and succulent plants, such as cacti, compromises ecosystem health and can result in changes in plant species composition that require expensive remediation interventions to restore ecosystem function, biodiversity and productivity. Historically, summer fires have been a major driver of open grassland and savanna ecosystems across the globe. Furthermore, there are both ecological and economic advantages to using fire to reduce invasive plants, such as mesquite brush and cacti, but the implementation of prescribed fire requires making some critical management decisions. Our model simulations illuminated the interactions and relative importance of the most important management decisions necessary for using summer fire to reduce such invasive plants. The use of results of a ranch-size field experiment to parameterize and corroborate our model and the close correspondence between the model output and experimental results provided a high level of confidence in the veracity of the simulation results and their relevance for ranch scale rangeland management decisions.

Our results indicate that the option of not applying fire negatively affects range condition, livestock production and ranching profitability over a 30-year timeframe, while all simulated fire treatments improved these parameters except when initial range condition was poor. Initial range condition and stocking rate were the major factors affecting both productivity and profitability, while the other factors over which managers have short-term control had a relatively minor impact. Our simulations also indicated that the highest level of profit consistent with maintaining or improving range condition was attained when individual animal production was 92–95% of maximum, a situation invariably associated with relatively low stocking rates. This provides a management principle for all rangelands where fire is a potential tool for reducing encroaching plants. The optimal stocking rates that maximize profitability while maintaining or improving rangeland resources may change due to climatic differences but, based on our simulation results, choosing a stocking level that achieves close to maximum performance per animal should apply to all such areas.

Finally, our simulations indicated that the use of summer burning is less likely to be negatively affected by the amount of mesquite cover than winter burning, which is supported by field research. This apparently vindicates the decision of many ranchers in the region who have chosen to use the more effective summer fires rather than winter fires to reduce mesquite and cactus, even though winter fires are less hazardous. These simulation results, in addition to previous research results, indicate that summer burning may lead to increased soil carbon levels, suggesting elevated carbon sequestration in burned areas compared to unburned areas. For these reasons, the use of prescribed summer fire as a rangeland ecosystem restoration and maintenance tool should be considered very seriously if not advocated in order to ensure the maintenance of good to excellent range condition for the continued delivery of rangeland ecosystem services upon which the wellbeing of human societies depend.

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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	Σ 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
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
Year	Year of simulation (i.e. 1,2, 3…. 30)	Years

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