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A simple ecological sustainability simulator (SESS) for stocking rate management on semi-arid grazinglands

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Abstract

We constructed a simple simulation model (SESS) of the dynamics of forage growth and standing crop and cattle production to evaluate the ecological sustainability of management alternatives for extensive cow-calf production systems in northeastern México and south Texas. Equations were written to estimate annual net primary production based on range condition, annual precipitation, and soil characteristics typical of the region. Simulations were conducted for annual precipitation levels of 300, 500, and 700 mm to estimate total and green standing crop dynamics, cattle grazing efficiency, and range condition trend for different stocking rates. The model-estimated stocking rates to achieve stable or slight improvement of range condition for the three precipitation levels were close to 58, 15, and 6 ha per animal-unit-year (AUY), respectively. With the model parameterized for precipitation and soil characteristics combined with the stocking rates recommended by COTECOCA (1979. Coahuila. Tipos de vegetación, sitos de productividad forrajera y coeficientes de agostadero. Secretaria de Recursos Hidráulicos. Comisión Técnico Consultiva para la Determinación Regional de los Coeficientes de Agostadero. México), we conducted 20-year simulations for three groups of range sites of Coahuila, México (annual precipitation: 1: 270 mm, 2: 351 mm and 3: 467

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mm). The trends of body condition score and range condition for years 5, 10, 15, and 20 were similar within each of the three groups. The stocking rates recommended by COTECOCA were too high for sustainability on range site groups with 270 and 351 mm annual precipitation. The simulated probabilities for pregnancy rates at different stocking rates for the three groups indicated that the stocking rates recommended by COTECOCA were too high to achieve pregnancy rates ⩾80% in 8 out of 10 years with no supplement in the form of hay or concentrated feeds. Model simulations suggested that, in the absence of supplemental feed, ecological sustainability and acceptable livestock production could be achieved simultaneously at light stocking rates.

Keywords: Models; Simulation; Grazinglands; Rangelands; Semi-arid zones; ANP; Sustainability; Range condition; Grazing; Cattle reproduction

1. Introduction

Complex, detailed models that simulate the biomass production and utilization of grassland ecosystems have been proposed as decision tools for grazingland management (e.g. Dix and Beidleman, 1969; Van Dyne, 1969; Wight, 1983; Wight and Skiles, 1987; Carlson and Thurow, 1992). Although the explicit representation of ecological processes at a fine level of detail in these models is scientifically interesting, the lack of adequate data bases to parameterize them and the complexity of their output have limited their application in grazingland management. The objective of our work has been to develop and evaluate a simple model that represents the basic ecological dynamics of grazingland systems. Both regional managers and individual producers should be capable of parameterizing the model based on information that is readily available. It produces output that is both understandable and useful to managers. We have focused our initial efforts on developing this model as a decision tool for stocking rate management on the semi-arid grazinglands of northeastern México and southern Texas, USA.

The Mexican states of Tamaulipas, Nuevo León, and Coahuila and the southern portion of Texas (Fig. 1) contain 45 million ha of grazinglands that are used primary for cow-calf production and wildlife-related recreation (Hanselka and Archer, 1998; Rodríguez et al., 1998). Precipitation in southern Texas generally occurs during spring and fall, with an annual average of 430 mm and a high coefficient of variation (0.35; Hanselka and Archer, 1998). Annual precipitation in northeastern México ranges from 100 to 1200 mm, but much of the area receives 300–700 mm (Ibarra et al., 1998). Stocking rates in southern Texas commonly are around 4.5 ha (Animal-Unit-Year, AUY)$^{-1}$ (Turner and Ducoing, 1998). The carrying capacity of grazinglands in northeastern México ranges from 1 ha AUY^{-1} in southern Tamaulipas to 45–80 ha AUY^{-1} in Coahuila and Nuevo Leon. This stocking rate gradient generally follows the precipitation gradient (Ibarra et al., 1998). Overstocking is considered the principal cause of desertification on these lands (Olivares and Ibarra, 1999; Redmon, 1999); high stocking rates reduce the amount of vegetation and water infiltration (Knight, 1999).

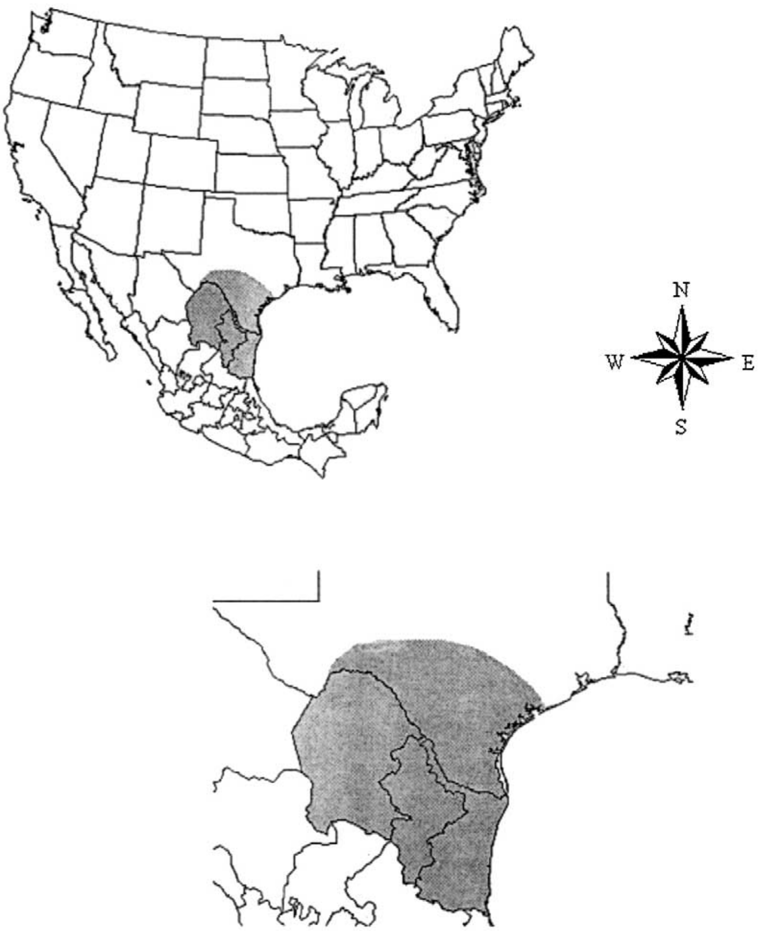

Fig. 1. Map of the system of interest, including the Mexican states of Coahuila, Nuevo León and Tamaulipas, and south Texas.

Failure to meet livestock reproduction goals on these semi-arid grazinglands most often results from inadequate daily energy intake during key phases of the production cycle. Supplemental feeds are expensive and feeding hay and concentrates frequently is not economically justified. Under these circumstances, successful cow-calf producers operating in severe, drought-prone environments must rely on two pervasive management practices: (1) correct stocking rate management and (2) controlled, properly timed, calving and breeding seasons. In southern Texas the breeding season usually occurs for 90 days or less during spring (Carpenter, 1998). The common recommendation for enhanced economic returns in extensive livestock husbandry in southern Texas is to maintain low production costs more than to improve productive performance of cattle (Turner and Ducoing, 1998).

Precipitation accounted for 92% of the variability in aboveground net primary production (ANPP) in central grassland region of USA but soil texture did not explain a significant proportion of the variability in ANPP (Lane et al., 1998). Biondini et al. (1998) reported that precipitation was the most important factor for ANPP and that the system was sustainable when grazing intensity left residues of 50% of ANPP.

The variable rainfall in semi-arid grazinglands poses a fundamental challenge to standard conceptions of carrying capacity. Carrying capacity is predicated on the notion that herbivores are controlled through the availability of forage, and forage availability is controlled by animal numbers; a pattern of negative feedback that eventually produces a stable equilibrium between animal and plant populations (Behnke and Scoones, 1993). Irreversible vegetation change may occur for a larger set of soils and climatic conditions when animal numbers are kept constant by human intervention, for instance by supplying additional food or water to herbivores when natural resources are scarce (Van de Koppel and Rietkerk, 2000). However, in semi-arid regions with highly variable rainfall, rainfall often limits forage availability and, hence, herbivore populations. Thus effective management is not a matter of adhering to a single, conservative stocking rate. Rather, it is a game of calculating probabilities "the object of which is to seize opportunities and to evade hazards, so far as possible" (Behnke and Scoones, 1993; Illius et al., 1998).

In this paper we describe a simple ecological sustainability simulator (SESS) for stocking rate management on the semi-arid grazinglands of northeastern México and southern Texas. SESS simulates forage production as a function of precipitation and soil characteristics; range condition as a function of grazing efficiency; and livestock performance as a function of forage standing crop, stocking rate, and energy requirements. We first present equations to estimate net primary production, then describe the structure and parameterization of SESS, and then evaluate the performance of each of the four submodels that comprise SESS. Finally, we demonstrate the application of SESS to evaluate long-term effects of various stocking rates on range condition and animal reproduction under precipitation regimes selected to be characteristic of northeastern México and southern Texas.

2. Estimation of aboveground net primary production

To relate annual aboveground net primary production (ANPP, kg dry matter ha^{-1} year^{-1}) to annual precipitation (PPT, mm year^{-1}), we used the concept of precipitation use efficiency (PUE, kg aboveground dry matter (DM) produced ha^{-1} mm^{-1} of precipitation-year^{-1}) proposed by Le Houreou (1984). We used soil characteristics (SC, unit-less index) to modify ANPP based on the potential productivity of the site and range condition (RC, unit-less index) to adjust estimates of ANPP for the proportion of ANPP that could be classified as forage.

$$\text{ANPP} = \text{PPT} \times \text{PUE} \times \text{RC} \qquad (1)$$

where:

$$\text{PUE} = \text{SC} + b_1 \times \text{PPT} \tag{2}$$

We estimated the parameters for the equation to calculate PUE via linear regression forced through the origin (i.e. with SC = 0) based on annual aboveground net primary production data from a variety of grazingland sites with mean annual precipitation between 300 and 700 mm. Analysis of PUE data from 10 sites in Africa (Le Houreou, 1984) and ANPP from 1795 sites in the southwestern United States (United States Soil Conservation Service, http://plants.usda.gov/esis/index.html) yielded $b_1 = 0.0084$ (df = 1,9, $R^2 = 0.96$) and $b_1 = 0.0084$ (df = 1,1794, $R^2 = 0.60$), respectively. We defined RC values of 0.5, 0.75, 1, and 1.25 as representing adjustments for ranges in "poor," "fair," "good," and "excellent" condition, respectively. This represents the greater proportion of ANPP that is forage for cattle as range condition increases. SC values were estimated in terms of soil depth and slope from Soil Conservation Service soil surveys for the 25 southernmost Texas counties (Table 1).

We evaluated the ability of Eqs. (1) and (2) to estimate ANPP for "poor," "fair," "good," and "excellent" range conditions by comparing the estimates generated by the equations to observations reported by COTECOCA (1979) for 127 range sites in the state of Coahuila in northeastern México. To parameterize SESS Eqs. (1) and (2) for each site, we set PPT equal to the annual precipitation reported by COTECOCA for that site and assigned RC values representing "poor," "fair," "good," and "excellent" corresponding to the range condition classes "pobre," "regular," "buena," and "excelente," respectively, identified by COTECOCA. We calculated a SC value based on the description of soil depth (profundidad de suelo) and slope (pendiente) provided by COTECOCA following the guidelines in Table 1. We multiplied the resulting estimate of ANPP by 0.25 to convert to "usable forage" (Kothmann et al., 1986) since COTECOCA reported forage production in terms of "forraje utilizable." Our estimates generally fell within the range of estimates of COTECOCA under all precipitation levels and range conditions (Fig. 2). Our estimated means, when averaged over all sites within each range condition class, were slightly higher for the excellent, good, and fair classes, and slightly lower for the poor class. The relatively random distribution of data points around the regression

Table 1
Descriptions of soil characteristics used to determine a soil depth factor (DF) and a slope factor (SF) to calculate the soil condition index (SC) according to the equation: SC = DF + SF

Characteristic	Description	DF or SF
Depth	< 25 cm	−0.5
	25–50 cm	0.0
	> 50 cm	0.5
Slope	< 15%	0.5
	15–35%	0.0
	> 35%	−0.5

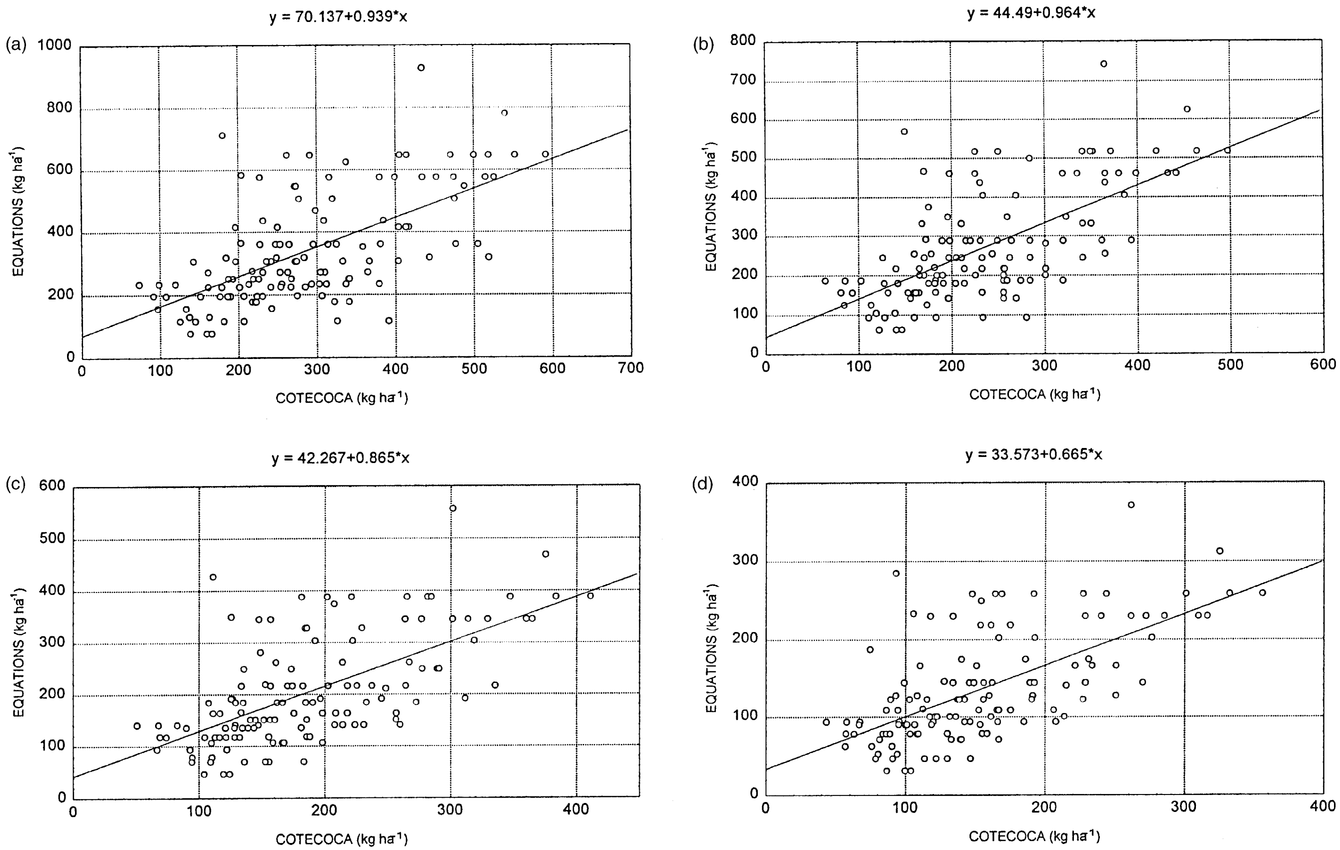

Fig. 2. Usable forage available (DM, kg ha^{-1} $year^{-1}$) for (a) "excellent," ($R^2=0.38$) (b) "good," ($R^2=0.41$) (c) "fair," ($R^2=0.40$) and (d) "poor" ($R^2=0.40$) range conditions at each of 127 range sites in the state of Coahuila, México. Survey estimated by the Comisión Técnico Consultiva para la Determinación de los Coeficientes de Agostadero (COTECOCA, 1979) and estimated by Eqs. (1) and (2).

lines indicates that ANPP estimates may be subject to field sampling problems and additional sources of variation that were not included in either model. Differences in seasonal climatic patterns for precipitation and temperature can affect values for PUE, but there was no major lack of fit evident in the data.

3. Simulation model description

We formulated SESS as a compartment model based on difference equations ($\Delta t = 1$ month) programmed in STELLA® 6.0 (High Performance Systems, Inc., Hanover, New Hampshire) to simulate the dynamics of standing crop forage, range condition, diet selection, and cattle production (Fig. 3). The forage submodel represents the dynamics of green and dry standing crop. ANPP is distributed across the months depending on the seasonal distribution of PPT and mean monthly temperature. Green standing crop is converted into dry standing crop via frosts and senescence. A fraction of senescent forage, representing senescence respiration and translocation, is lost with the remainder transferred to dead standing crop. Green standing crop also is lost due to consumption, trampling, and dung deposition by cows. Dry standing crop is lost due to consumption, trampling and dung deposition by cows, and via decomposition. The range condition submodel represents changes in range condition based on the proportion of ANNP consumed by cattle. The diet selection submodel estimates the proportions of green and dry forage in cattle diets based on preference and harvestibility, as described by Blackburn and Kothmann (1991). The cattle production submodel simulates dry matter intake, body condition scores of cows (National Research Council of the United States, NRC, 2000), and herd pregnancy rates. Grazing efficiency is calculated as the proportion of ANPP consumed by cattle. Condition is simulated as a function of grazing efficiency and annual PPT. A compendium of parameters and variables is reported in the Appendix.

3.1. Forage submodel

3.1.1. Green standing crop (GSC)

Dynamics of green standing crop (kg dry matter ha^{-1}) are represented as:

$$\mathrm{GSC}(t+1) = \mathrm{GSC}(t) + (\mathrm{MNPP} - \mathrm{GSCC} - \mathrm{GSCF} - \mathrm{GSCS}) \times \Delta t \quad (3)$$

where MNPP is monthly aboveground net primary production, and GSCC, GSCT, GSCF, and GSCS represent losses due to consumption by cattle, trampling and dung deposition by cattle, frosts, and senescence, respectively, all in kg dry matter ha^{-1} $month^{-1}$.

$$\mathrm{MNPP} = \mathrm{ANPP} \times \mathrm{GI}_i \quad (4)$$

where ANPP is calculated using Eqs. (1) and (2) as above, except that PPT is a random variable (RPPT) drawn at the beginning of each year of simulated time

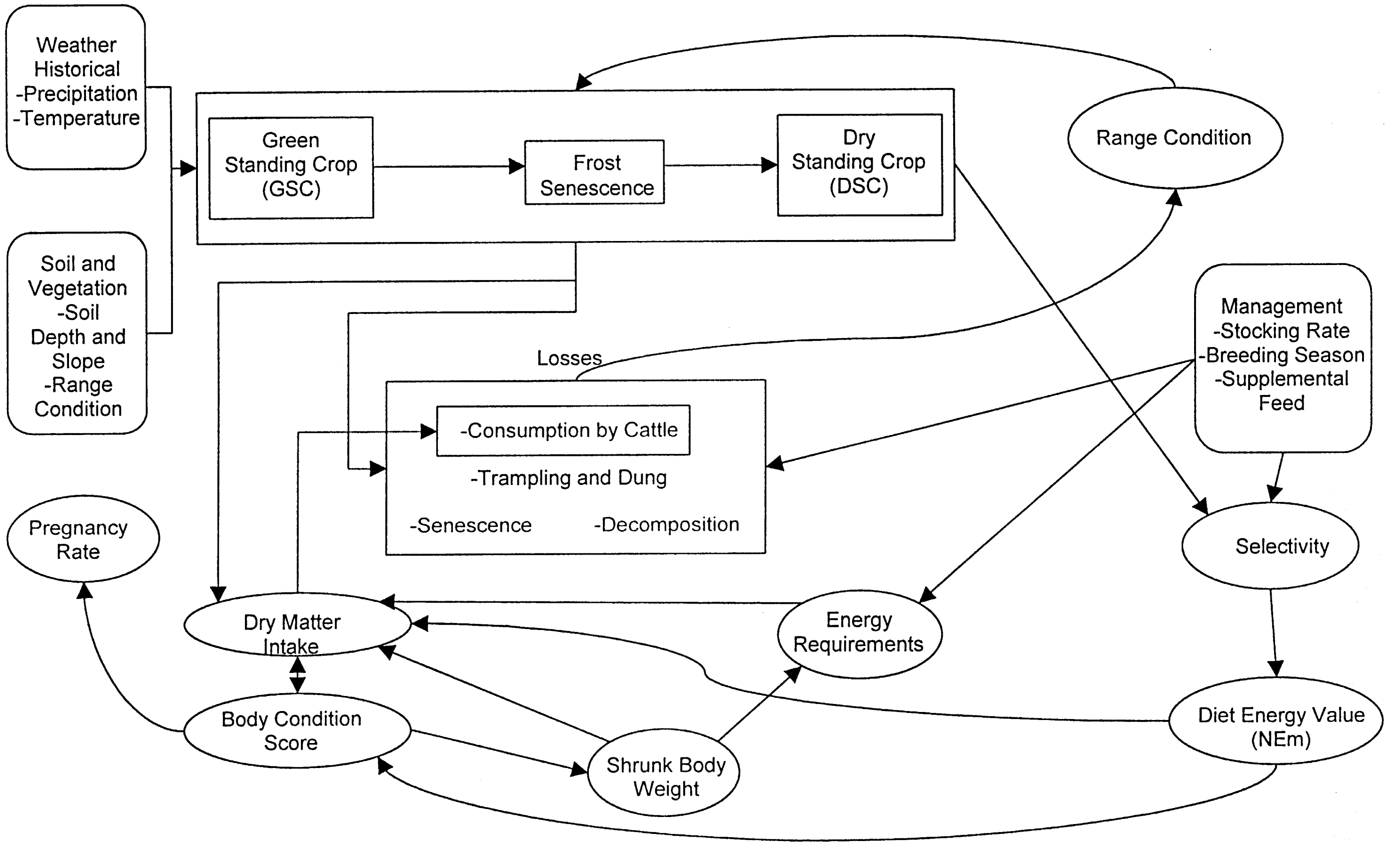

Fig. 3. Diagram of a simple systems model representing forage and cattle production in northeastern México and south Texas.

from a normal distribution. The distribution was parameterized with a mean equal to the historical mean PPT of the site being simulated and a coefficient of variation (CV) calculated as CV = 0.409−0.0002×PPT via linear regression (df = 1,75; $R^2 = 0.075$; $P < 0.016$) based on data of Le Houreou et al. (1988). GI_i is a growth index representing the proportion of ANPP that occurs during the ith month of the year based on historical mean monthly temperature (MT_i, C) and precipitation (MPP_i, mm month^{-1}) of the site being simulated, and the base temperature (BT) for C_4 plants (10 °C, Kiniry et al., 1991).

$$GI_i = (TI_i \times PPI_i) \quad \Sigma(TI_i \times PPI_i)^{-1} \tag{5}$$

where TI_i is the temperature index and PPI_i is the precipitation index for month i.

$$TI_i = (MT_i - BT) \quad \Sigma(MT_i - BT)^{-1} \tag{6}$$

$$PPI_i = (MPP_i) \quad (\Sigma MPP_i)^{-1} \tag{7}$$

For the simulations in this paper we used the historical monthly means for temperature and precipitation of the weather stations in the Mexican state of Coahuila. The resultant GI monthly coefficients were: 0.011, 0.016, 0.023, 0.049, 0.131, 0.150, 0.194, 0.158, 0.176, 0.061, 0.015, 0.015 from January to December, respectively.

Green forage consumption by cattle (GSCC) is calculated as:

$$GSCC = WRI \times SD_1 \times 30 \times GFD \tag{8}$$

where WRI is the weighted average of restricted intake [RI; Eq. (20)] for the three cow cohorts, SD_1 is stocking density (animal-units ha^{-1} day^{-1}) and GFD is green forage in diet [Eq. (17)].

Forage losses due to trampling and dung deposition (GSCT) assume a linear relationship between total standing crop (TSC = GSC + DSC) and trampling loss (TL, DM kg animal-unit^{-1} day^{-1}) so that when TSC = 0, TL = 0 and when TSC = 4000, TL = 3.

$$GSCT = TL \times SD_1 \times 30 \times GSC/TSC \tag{9}$$

Losses due to frosts are represented as:

$$GSCF = F \times (GSC - GSCC - GSCT) \tag{10}$$

where F is an index empirically related to mean monthly temperature (Fig. 4a).

Loss due to senescence is represented as:

$$GSCS = S \times (GSC - GSCC - GSCT - GSCF) \tag{11}$$

where S is an index related to month of the year (Fig. 4b).

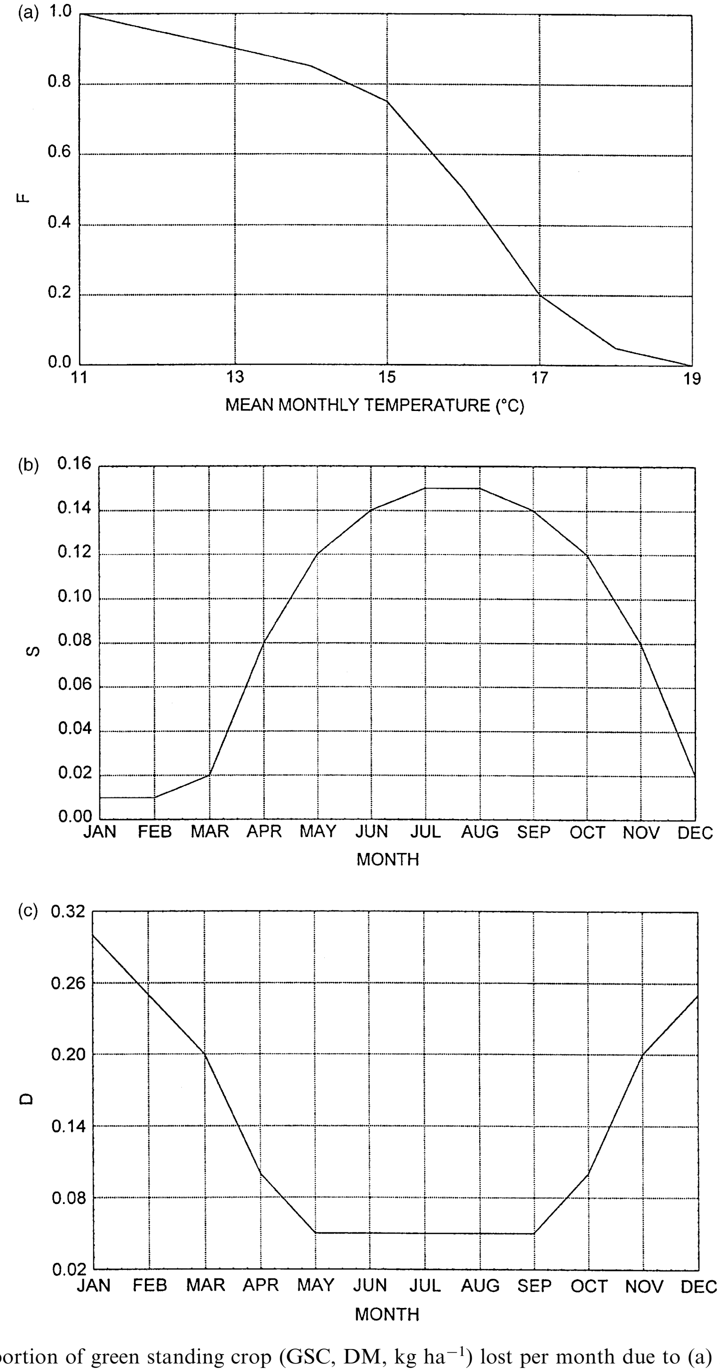

Fig. 4. Proportion of green standing crop (GSC, DM, kg ha^{-1}) lost per month due to (a) frosts (F), (b) senescence (S), and (c) dry standing crop (DSC, DM, kg ha^{-1}) lost per month to due long-term decomposition (D) (expert opinion: M. M. Kothmann, College Station, TX).

3.1.2. Dry standing crop (DSC)

Dynamics of dry standing crop (kg dry matter ha^{-1}) are represented as:

$$\mathrm{DSC}(t+1) = \mathrm{DSC}(t) + [\mathrm{GSCF} + (\mathrm{GSCS} \times 0.75) - \mathrm{DSCC} - \mathrm{DSCT} - \mathrm{DSCD}] \times \Delta t \tag{12}$$

where GSCF and GSCS are green forage frosted and green forage senescence and DSCC, DSCT, and DSCD represent losses due to consumption by cattle, trampling and dung deposition by cattle, and long-term losses due to decomposition, respectively, all in kg dry matter ha^{-1} month^{-1}.Loss due to consumption by cattle (DSCC) considers the same parameters that Eq. (8) as:

$$\mathrm{DSCC} = \mathrm{WRI} \times \mathrm{SD}_1 \times 30 \times (1 - \mathrm{GDF}) \tag{13}$$

We assume that loss due to trampling and dung deposition (DSCT, kg ha^{-1} month^{-1}) by each animal-unit day^{-1} is positively related to total standing crop (TSC) as in Eq. (9).

$$\mathrm{DSCT} = \mathrm{TL} \times \mathrm{SD}_1 \times 30 \times (\mathrm{DSC}/\mathrm{TSC}) \tag{14}$$

Loss due to long-term decomposition is represented as:

$$\mathrm{DSCD} = D \times (\mathrm{DSC} - \mathrm{DSCC} - \mathrm{DSCT}) \tag{15}$$

where D is an index related to month of the year (Fig. 4c).

3.2. Range condition submodel

To represent long-term changes in range condition (RC) resulting from different stocking rates, we estimated an annual adjustment (UE) to RC as a function of annual PPT and grazing efficiency (GE), that is, the percentage of ANPP consumed by cattle during the previous year (expert opinion: M.M. Kothmann, College Station, TX; Fig. 5). GE is calculated as reported by Scarnecchia [1988, Eq. (1)]. We considered that GE levels of 10.0, 12.5, and 15.00% of ANPP correspond to total forage disappearance values of 40, 50, and 60%, which we assume produce no change in RC in areas of 300, 500, and 700 mm annual precipitation, respectively. Esselink et al. (1988, cited by FAO, 1991) suggested that forage lost to grazing is two to three times GE. The values for GE may seem low in comparison to utilization estimates based on total dry matter disappearance of standing crop; however, it should be noted that GE is based on forage consumption and ANPP, variables that cannot be measured directly in the field but are calculated by the model (Scarnecchia and Kothmann, 1986). Thus:

$$\mathrm{RC}(t+1) = \mathrm{RC}(t) + (\mathrm{RC} \times \mathrm{UE}) \times \Delta t \tag{16}$$

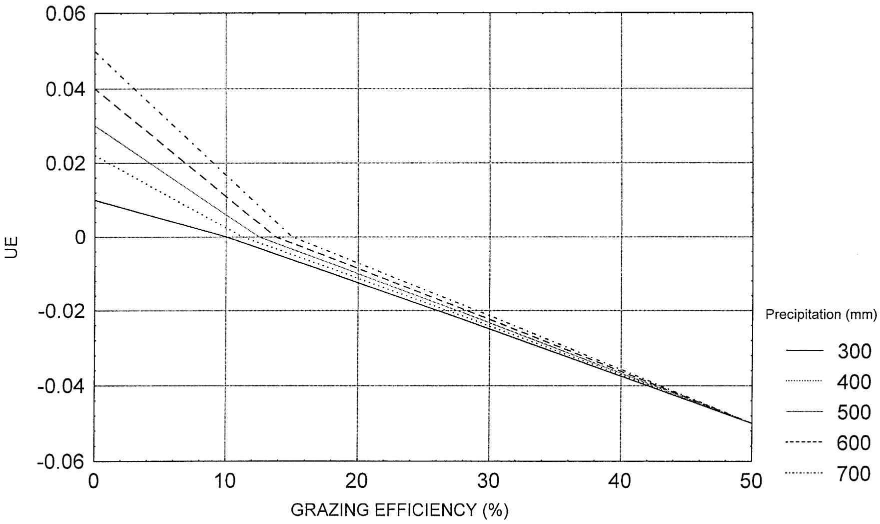

Fig. 5. Proportional annual change (UE) in range condition (RC) resulting from different levels of mean annual precipitation (mm) and grazing efficiency (percentage of ANPP consumed by cattle) (expert opinion: M. M. Kothmann, College Station, TX).

3.3. Diet selection submodel

We based the diet selection portion of this submodel on a model developed by Blackburn and Kothmann (1991). This submodel estimates the proportion of green forage in the diet (GFD) as the product of cattle preference for green forage (PGF) and its harvestability (HGF).

$$\text{GFD} = \text{PGF} \times \text{HGF} \tag{17}$$

$$\text{HGF} = (1.1 \times \text{GSC}) \quad (\text{Kms} + \text{GSC})^{-1} \tag{18}$$

where GSC is green standing crop and Kms is a threshold that changes with ANPP potential as:

$$\text{Kms} = (111.9)/[1 + 106.2 \times e^{(-0.0022 \times \text{RPPT} \times \text{PUE})}] \tag{19}$$

The ability of grazing animals to harvest green forage is a function of the density and structure of the vegetation. Above some upper threshold, green forage availability does not limit intake. However, as the availability of green forage decreases below that threshold, its harvestability decreases. This relationship is represented as a Michaelis-Menten function (Blackburn and Kothmann, 1991; Finlayson et al., 1995). Kms×10 represents the inflection point of the harvestability curve; in other words, the restriction to green forage harvest is present when its availability is $\leqslant$90,

$\leqslant 500$, $\leqslant 1000$, and $\leqslant 1100$ kg ha^{-1} of green forage for range sites and years with ANPP of 1000, 2000, 3000, and 4000 kg ha^{-1} year^{-1}, respectively.

The rationale for the positive relationship between ANPP and the selectivity parameter (Kms) is that mesic sites with high ANPP have a more uniform stand with a greater ungrazable residual than more arid sites where green forage is clumped resulting in less ungrazable residual.

The green forage preference (PGF) is calculated according to Blackburn and Kothmann (1991), considering dry matter digestibility of 0.7 and 0.5, and crude protein contents of 0.12 and 0.06, for green and dry standing crop, respectively.

The dietary net energy for maintenance (DNEm, Mcal kg^{-1}) has a linear relationship with the proportion of green forage in the diet (GFD); when GFD = 0, DNEm = 0.7, and when GFD = 0.78, DNEm = 1.48. These values are estimated from Kothmann et al. (1986).

3.4. Cattle production submodel

Energy requirements for maintenance (Rm), pregnancy (Rpreg), lactation (RL), and grazing activity (Rmact) are calculated separately for each monthly cohort of cows according to NRC (2000, pp. 11, 114–117). Cohorts are defined by the month of conception. Potential voluntary intake (PVI) is calculated according to NRC (2000, p. 119), and restrictions to PVI due to harvestability (IRC) are calculated using a Michaelis-Menten function (Blackburn and Kothmann, 1991) similar to the green forage harvestability function of the selectivity submodel [Eq. (18)]. Then, the restricted daily dry matter intake (RI, kg DM head^{-1} day^{-1}) is calculated as:

$$\mathrm{RI} = \mathrm{PVI} \times \mathrm{IRC} \tag{20}$$

Minson (1987) reported that cattle can achieve voluntary intake when dry matter availability is above 1000–1500 kg ha^{-1}, however, Holmes (1987) estimates this threshold as 2500 kg ha^{-1} and NRC (2000) at 1150 kg ha^{-1}. We use a variable threshold (Kmh) that is positively related to ANPP because less harvestable plant parts may be the only residual forage at higher standing crop values at sites with higher ANPP potential. Possible restrictions (IRC) of potential voluntary intake due to total standing crop availability (TSC) are calculated as:

$$\mathrm{IRC} = (1.1 \times \mathrm{TSC}) \quad (\mathrm{Kmh} + \mathrm{TSC})^{-1} \tag{21}$$

where TSC is total standing crop (kg DM ha^{-1}).

Kmh changes according to:

$$\mathrm{Kmh} = 73.7 + (0.0086 \times \mathrm{RPPT} \times \mathrm{PUE}) + [6.02\mathrm{E}^{-7} \times (\mathrm{RPPT} \times \mathrm{PUE})^2] \tag{22}$$

Potential voluntary intake is restricted when TSC is lower than or equal to 880, 1150, 1550, and 2050 kg ha^{-1} for sites and years with ANPP of 1000, 2000, 3000, and 4000 kg ha^{-1} year^{-1}, respectively.

Maintenance energy intake is estimated as the product of restricted daily dry matter intake (RI) and diet energy concentration for maintenance (DNEm, Mcal kg^{-1}), which depends on the proportions of green and dry forage in the diet [GFD; Eq. (17)].

Change in body condition score (BCS, unit-less index with values between 1 and 9) for each cohort of cows is based on energy for maintenance balance (energy intake-energy required) according to NRC (2000, pp. 33–37). Shrunk body weight of each cohort (SBW, kg $head^{-1}$) is calculated based on BCS:

$$SBW = MW \times PW \tag{23}$$

where MW is mature weight (kg) at BCS 5 and PW are coefficients related to BCS from NRC (2000; p. 36, Tables 3–5).

Pregnancy rate (PREGNANCY, %) of the herd is calculated based on the weighted average of the BCS of the monthly cohorts (WBCS). The expected PREGNANCY percentages for WBCS 1–9 are: 0, 5, 25, 65, 82.5, 87.5, 93, 93 and 85, respectively (http://texnat.tamu.edu/ranchref/guide/h_tbl4.htm).

4. Model evaluation

Since we developed the diet selection and cattle production submodels of SESS based on equations in Blackburn and Kothmann (1991) and the NRC (2000), with only minor modifications, we focused model evaluation efforts on the forage and range condition submodels. Eqs. (1) and (2) used in the forage submodel to estimate ANPP provide good estimates for different range sites and range condition classes. Differences in ANPP estimates between SESS and COTECOCA (1979) may be partially due to sampling error, and/or differences among COTECOCA surveys (different seasons under different climatic conditions and intensities of grazingland utilization). SESS can provide more specific estimates of carrying capacity by adjusting the grazing efficiency values close to 10–18% of ANPP for areas of 300 and 700 mm annual precipitation, respectively. These values are similar to those reported by Kaplan (1984, as cited by FAO, 1991). Field research will be needed to verify grazing efficiency values in relation to range condition change over time.

The range condition submodel, when parameterized with an initial range condition class of "good," SC = 0, and an annual precipitation of 500 mm, suggests a slight improvement (5–10%) in range condition over a 20-year period at a stocking rate of 16 ha AUY^{-1}. This is similar to the slight improvement (5–0%) in range condition that can be calculated for a stocking rate of 14 ha AUY^{-1}, assuming a grazing efficiency of 14%, using the estimated dry matter forage yield for a clay loam range site (SC = 1) in mid-good condition in the 500 mm precipitation zone of south Texas (Hamilton et al., 1986). The higher estimated stocking rates for range improvement in south Texas results can be explained based on differences in soil characteristics; the simulated soil (SC = 0) was less productive than the south Texas soil (SC = 1) upon which calculations were based (Hamilton et al., 1986).

5. Applications

Although the model is capable of representing changes in stocking rate, breeding season, and amount of feed supplementation, the objective of this paper is to evaluate the long-term effect on range condition and animal production of stocking rates fixed by human intervention without supplemental feed, as this is a common occurrence in many developing countries. We hypothesized that range condition can be sustained or improved and acceptable animal production can be achieved on semiarid grazinglands with fixed, conservative stocking rates and no energy supplementation.

5.1. Simulating the effect of precipitation

We simulated the precipitation effect because it is the most important variable that drives forage production, carrying capacity and cattle performance and to show the responses of the model in the range of interest (300–700 mm). In this section we show the responses for total standing crop (TSC), green standing crop (GSC), grazing efficiency (GE) and range condition (RC). The standing crop variables are important to give information about the inputs for the cattle performance in the next section. Grazing efficiency is the variable that drives range condition and range condition is the key response to evaluate ecological sustainability. Simulating and reporting these main variables that drive sustainability and cattle performance and evaluating their interrelationships achieves our objectives for understanding SESS as a stocking rate management decision aid.

We present the monthly means and standard deviations of total standing crop (TSC) and green standing crop (GSC) during the third simulated year based on 100 replicates for each scenario with mean annual precipitation of 300, 500, and 700 mm (Fig. 6). The initial range condition and soil characteristics were held constant at good and regular classes, respectively (RC = 1, SC = 0). The stocking rates used were moderate for the 3 scenarios, respectively, to avoid changes in range condition. Standing crop values follow expected trends with higher GSC in the summer. Total standing crop also differed greatly among precipitation levels. Maximum values for TSC occurred in October–November with close to 800, 1950, and 3800 kg DM ha^{-1} for 300, 500, and 700 mm, respectively.

The grazing efficiency (total intake by cattle/ANPP,%) and the change in range condition also were simulated for different stocking rates for 20 years with 100 replicates for each precipitation level and stocking rate combination. The soil characteristics were constant at regular class (SC = 0) and all the simulations started in good range condition. The breeding season was April, May, and June.

Grazing efficiency percentages to achieve a sustainable range condition were in the range of 10–18% of ANPP (Fig. 7). Range condition was more responsive to stocking rate as precipitation increased (Fig. 8). Stocking rates to maintain or improve range condition were 58, 15, and 6 ha AUY^{-1} for areas of 300, 500, and 700 mm PPT, respectively. Dyksterhuis (1975) reported long-term average moderate stocking rates of 19, 11, and 7 ha AUY^{-1} as related to annual precipitation of 300,

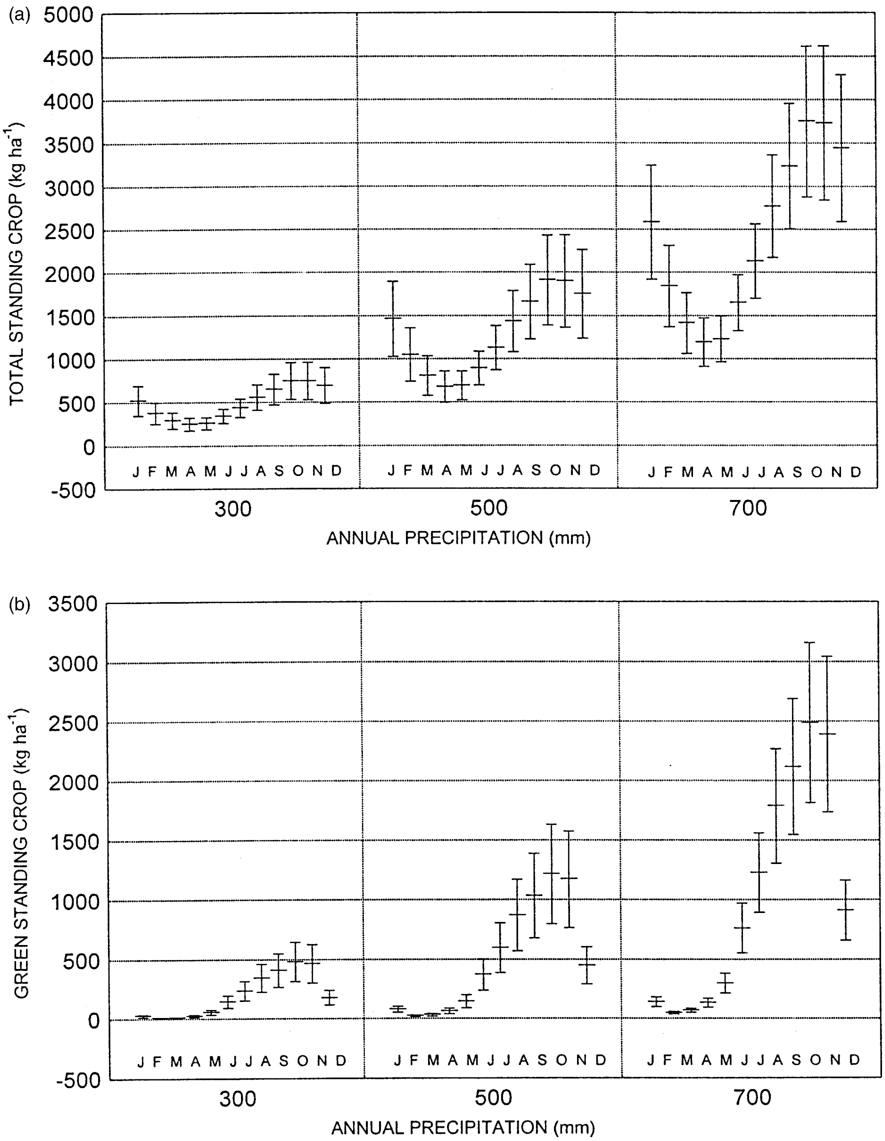

Fig. 6. Seasonal dynamics (mean ± SD; $n = 100$) for (a) total standing crop (TSC), and (b) green standing crop (GSC) simulated under different precipitation levels with a moderate stocking rate (initial range condition = good, and SC = regular).

500, and 700 mm, respectively. Using the conventional method to estimate carrying capacity ($CC = (450 \times 0.03 \times 365)/ANPP \times 0.25$) from the ANPP estimated by the Eqs. (1) and (2), we obtain estimates of 27, 10, and 5 ha AUY^{-1} for the same scenarios, but this method does not consider variability of precipitation as does the model. The difference between these estimations and model estimations increases as precipitation

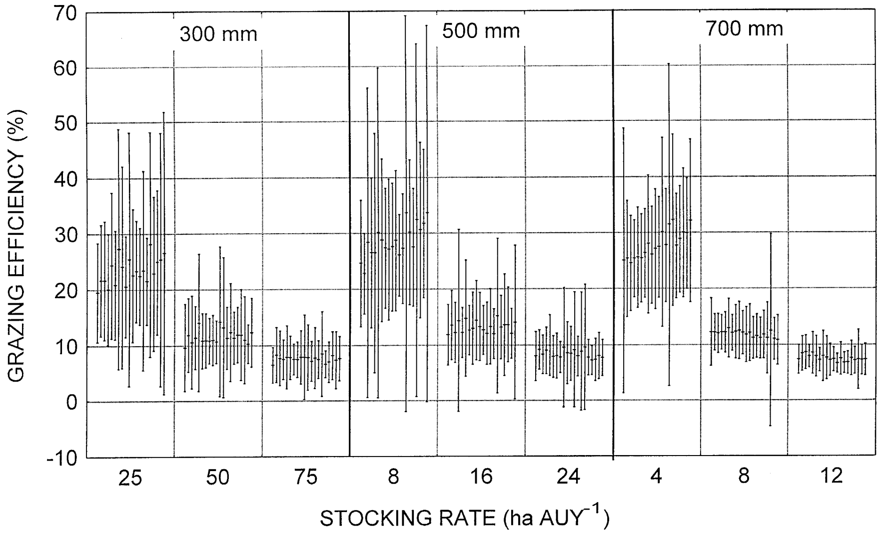

Fig. 7. Grazing efficiency (%, mean±SD; $n = 100$) over 20 years simulated under different precipitation levels and stocking rates (each group of bars represents years 1–20).

decreases basically due to several reasons: the low precipitation areas have higher precipitation variability, and the utilization threshold for no change in range condition and the positive response to low utilization levels are lower; and the model considers no supplemental feed and commonly these practices are more frequently found in low precipitation areas. The Dyksterhuis (1975) data are from research stations and it is probable that supplemental feed was used.

These results suggest that using 25% of ANPP as usable forage as a constant to estimate carrying capacity is inadequate. It should be noted that field estimation of ANPP generally consists of measurement of standing crop at some point in time. Standing crop represents a state variable with varying rates of inflow and outflow, thus it is never a measure of ANPP as calculated by SESS (Scarnecchia and Kothmann, 1986). Model output suggested that for carrying capacity estimations we should consider grazing efficiency close to 10% of ANPP for areas of 300 mm and 18% of ANPP for areas of 700 mm. The model results were similar to those reported by Kaplan (1984, as cited by FAO, 1991) with grazing efficiency values of 10–25% for low-input pastoral systems with cattle and sheep. Smith et al. (1998) had reported that for sub-tropical Queensland, Australia "safe utilization" (eaten/grown×100) for sustainability is close to 20% of ANPP and that this value does vary from region to region.

5.2. Simulating the grazinglands in Coahuila

The simulated variables in this section were body condition score, range condition, and probabilities for pregnancy rate. Pregnancy rate is an indicator of sustainability

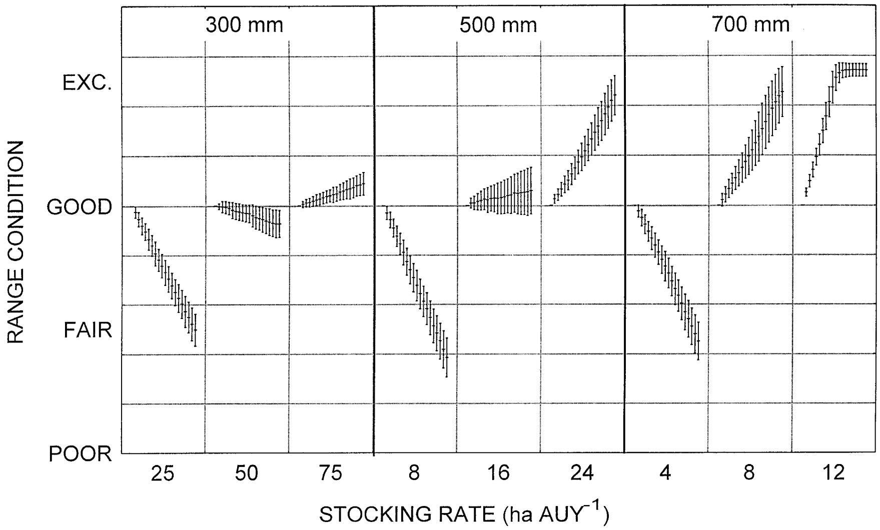

Fig. 8. Changes in range condition (mean±SD; $n=100$) over 20 years simulated under different precipitation levels and stocking rates (each group of bars represents years 1–20).

of the cattle production enterprise and we are interested in the relationships between these three variables.

5.2.1. Body condition score and range condition

We ran 100 replicates of 20-year simulations for each of three groups of grazing-lands in Coahuila at the stocking rates recommended by COTECOCA (1979) for good range condition (initial RC = 1). The breeding season was from April to June. To parameterize the simulation model, we assigned the 127 range sites in Coahuila reported by COTECOCA (1979) into three groups with relatively low, medium, and high mean annual precipitation (PPT). For each group, we calculated means for PPT (mm), SC (based on reported soil depths and slopes and Table 1), and stocking rate (SR; ha AUY^{-1}) recommended for these range sites by COTECOCA. We parameterized the model to represent each of the three groups of range sites: Group 1: $n=55$, PPT = 270, SC = 0.26, SR = 30.2; Group 2: $n=37$, PPT = 351, SC = 0.08, SR = 22.6; Group 3: $n=35$, PPT = 467, SC = 0.22, SR = 17.8.

Simulation results suggest that stocking rates recommended by COTECOCA for sites in groups 1 and 2 (mean PPT of 270 and 351 mm) are too high, however, the stocking rate for sites in group 3 (mean PPT of 467 mm) resulted in acceptable trends for BSC and improvement in RC (Figs. 9 and 10).

For the three range site groups, BCS followed similar trends as RC. Although these variables are calculated independently, the similar responses for BCS and RC resulted because increased stocking rate reduced forage availability, harvestability, diet quality, and DM intake. BCS is driven by DM intake and energy content, which are controlled by standing crop availability (TSC) and quality (GSC/DSC). Grazing efficiency drives RC. These results support the hypothesis that in systems where

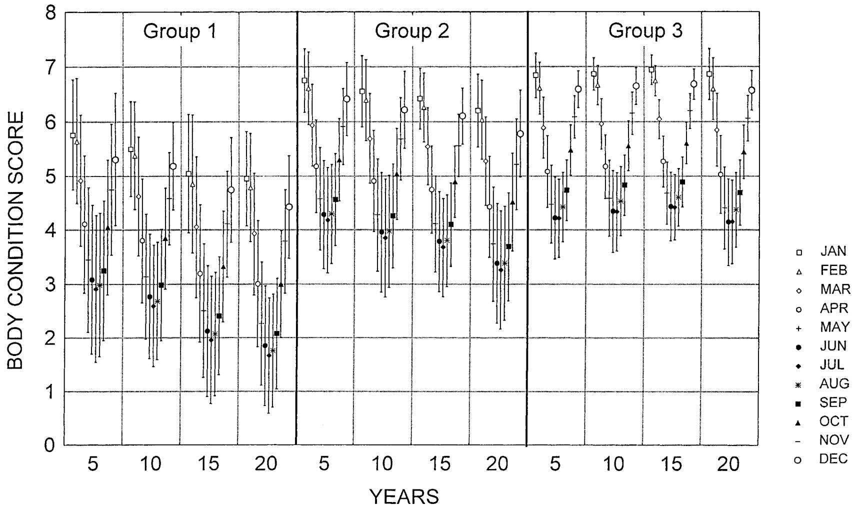

Fig. 9. Long-term (20-year) and seasonal trends in body condition score (mean±SD; $n=100$) simulated under the recommended stocking rates (SR, ha AUY^{-1}) and mean range site characteristics (soil characteristics index, SC: mean annual precipitation (mm), PPT) reported by the Comisión Técnico Consultiva para la Determinación de los Coeficientes de Agostadero (COTECOCA) for grazinglands in Coahuila. Groups: (1) $n=55$, PPT = 270, SC = 0.26, SR = 30.2; (2) $n=37$, PPT = 351, SC = 0.08, SR = 22.6; (3) $n=35$, PPT = 467, SC = 0.22, SR = 17.8.

herbivore numbers are kept constant by human intervention, for instance by supplying supplemental food when natural resources are scarce, deterioration in RC may occur faster than in systems where vegetation density determines herbivore population size (Van de Koppel and Rietkerk, 2000). Following these criteria, the best management option in semiarid grazinglands is to adjust the size of the animal population to maintain a balance with natural food availability. However, the model suggests that maintaining a constant, appropriate stocking rate can be more important than making annual adjustments in stocking rate. SESS predictions that a constant light stocking rate is compatible with sustaining range condition are compatible with observations reported by range scientists with extensive field experience. BCS and pregnancy rate are good indicators of food quality and availability relative to animal demand and the model suggests that when stocking rates are at a level such that cattle have acceptable pregnancy rates with no energy supplementation, range condition should be improving.

5.2.2. Pregnancy rate probabilities

We conducted 100 replicates of 20-year simulations of pregnancy rates for alternative cattle stocking rates under good initial range conditions (initial RC = 1) using the same means described for the three groups of sites defined in the previous section, including the stocking rate recommended by COTECOCA. Because precipitation and hence forage available for grazing are variable, we reported pregnancy rates as a probability of occurrence.

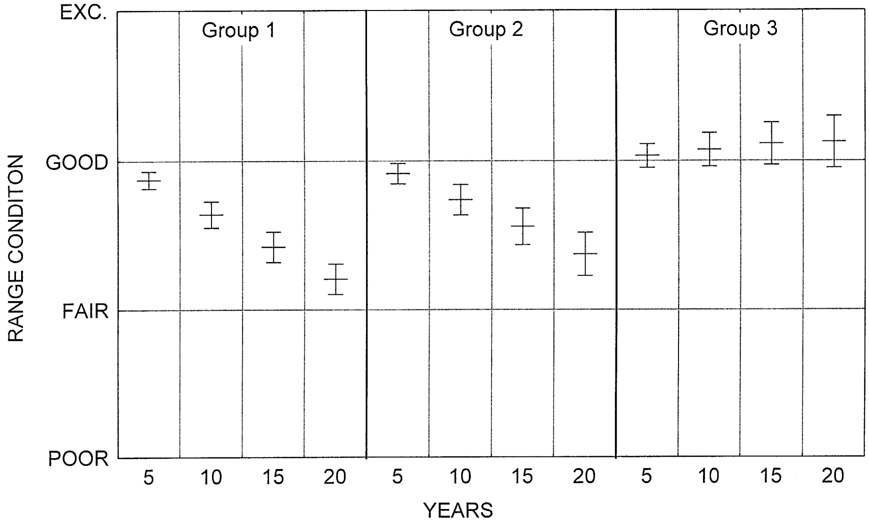

Fig. 10. Long-term (20-year) trends in range condition (mean ± SD; $n = 100$) simulated under the recommended stocking rates (SR, ha AUY^{-1}) and mean range site characteristics (soil condition index, SC: mean annual precipitation (mm), PPT) reported by the Comisión Técnico Consultiva para la Determinación de los Coeficientes de Agostadero (COTECOCA) for grazinglands in Coahuila. Groups: (1) $n = 55$, PPT = 270, SC = 0.26, SR = 30.2; (2) $n = 37$, PPT = 351, SC = 0.08, SR = 22.6; (3) $n = 35$, PPT = 467, SC = 0.22, SR = 17.8.

Simulated pregnancy rates indicate that the stocking rates recommended by COTECOCA for the three groups (30.2, 22.6 and 17.8 ha AUY^{-1}, for groups 1–3, respectively) are too high to achieve the targeted 80% pregnancy rate in 8 out of 10 years when no supplements are provided (Fig. 11). The target pregnancy rate is achieved at simulated stocking rate of roughly 22 ha AUY^{-1} for group 3 (PPT = 467 mm, SC = 0.22; Fig. 11c) and 27 ha AUY^{-1} for group 2 (PPT = 351 mm, SC = 0.08; Fig. 11b), and cannot be achieved even at 100 ha AUY^{-1} for group 1 (PPT = 270 mm, SC = 0.26; Fig. 11a).

6. Discussion

In México, the COTECOCA surveys (one per state) are the principal guide for stocking rate management decisions on grazinglands. COTECOCA recommendations are based on limited amounts of field data combined with expert opinion. They are limited in that they report average values for variables that are dynamic across seasons and years. This simulation study using SESS revealed two major problems with the use of this "conventional" approach to estimating carrying capacity: (1) it is difficult to estimate the correct ANPP for extensive grazingland areas, and (2) it uses a constant value for grazing efficiency (25%).

The similar trends for BCS, pregnancy rates, and RC for the three groups of range sites in Coahuila suggest that acceptable livestock production and ecological

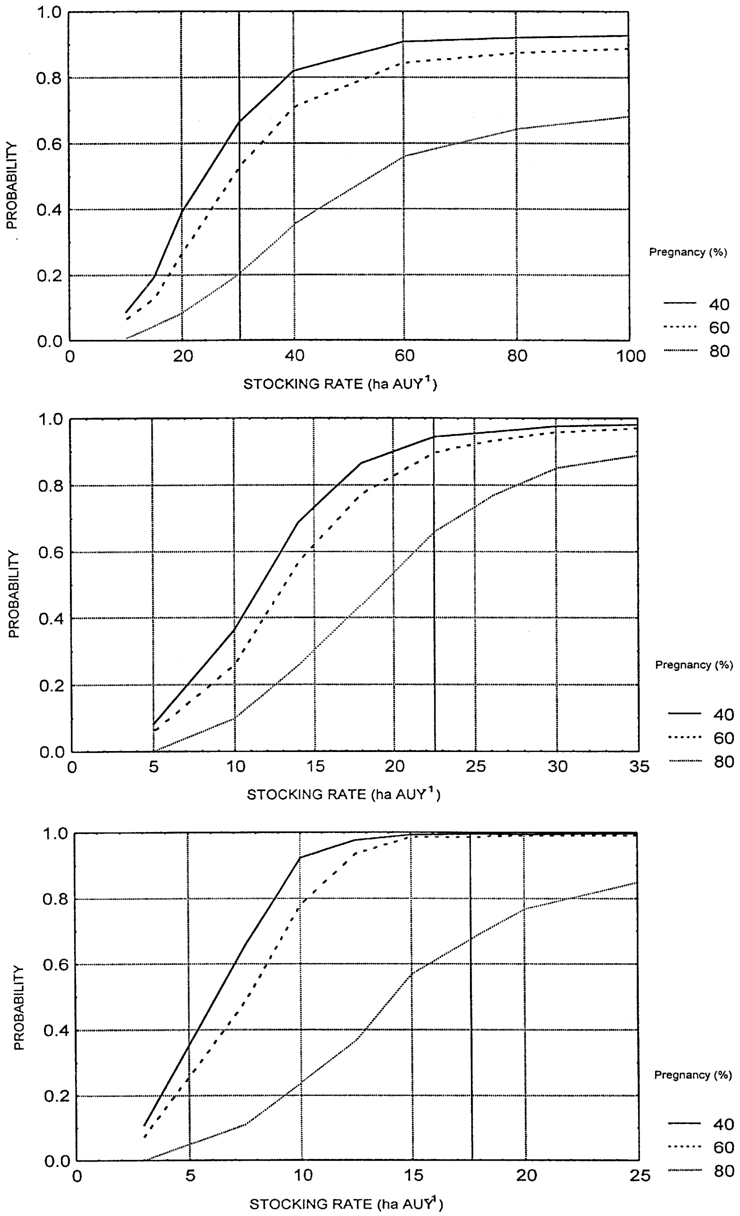

Fig. 11. Probabilities of achieving at least the indicated pregnancy rates simulated under different stocking rates (SR, ha AUY^{-1}) and mean range site characteristics (soil condition index, SC: mean annual precipitation (mm), PPT) reported by the Comisión Técnico Consultiva para la Determinación de los Coeficientes de Agostadero (COTECOCA) for grazinglands in Coahuila. Probabilities are based on 100 replicate, 20-year simulations. Groups: (1) $n=55$, PPT = 270, SC = 0.26; (2) $n=37$, PPT = 351, SC = 0.08; (3) $n=35$, PPT = 467, SC = 0.22. Stocking rates recommended by COTECOCA for groups 1–3 are 30.2, 22.6, and 17.8 ha AUY^{-1} respectively and are represented by vertical solid lines.

sustainability are achieved at similar stocking rates. Stocking rates that promote an acceptable pregnancy rate also will promote an improvement in range condition. Stocking rate recommendations estimated by SESS appear to be low, but we should consider that they are without supplemental feed. Supplemental feed can sustain high animal production at high stocking rates, but this practice can produce intensive grazingland utilization that will reduce range condition. Thus, supplementation can mask the natural relationship between animal population and forage availability. We will test the hypothesis that supplemental feeding can lead to deterioration in range condition in a subsequent paper.

We believe that the current version of SESS could be used to make stocking rate recommendations for grazinglands in northeastern México and southern Texas. Use of SESS over a period of years for a variety of different sites will identify if there are additional variables that should be included to provide more robust predictions. An iterative process of prediction with the model, collection of field data, and adjustment of model structure and parameters will lead to a more robust model that could serve as a general decision support tool to improve decision-making of land managers and policy makers who recommend and set stocking rates for arid and semiarid grazinglands.

Our overall objective in this paper has been to explore the possibility of developing a simple model representing the basic ecological dynamics of grazinglands, which can be parameterized based on information that is readily available and which produces output at a level of aggregation that is useful to both regional managers and individual producers. Philosophically, our modeling approach is to develop the simplest model of the system of interest and then, through experience and testing in the field, to determine if additional components could improve model performance. An alternative modeling approach would have been to logically decompose the important ecological processes, which we represented at a high level of aggregation, into more detailed sub-processes that, arguably, would be more amenable to direct field experimentation.

The use of increasingly detailed quantitative models as decision making tools for management of grazinglands and natural resources has drawn attention to key uncertainties arising at each finer level of detail. However, three problems are inherent in the more detailed approach: (1) the number of parameters grows exponentially as a process is decomposed into finer details, (2) small errors in the estimation of individual parameters can have large cumulative effects on model performance, and (3) ultimately, predictions from the detailed model still must be tested by reference to, and experiments conducted at, the higher levels of aggregation in which regional managers and individual producers are interested. Thus, while simulation models containing finer levels of details are attractive to researchers, they have found little application in the management setting.

Managers need models that are based on parameters that can be observed and measured in the field setting. These models must be flexible, allowing the manager to make adjustments based on monitoring data. Thus, we agree with Walters' (1986) call for an adaptive approach to resource management, not only in terms of viewing management itself as experimentation at the highly aggregated level of the intact system, but also in terms of developing management models that can be parameterized using information resulting from such management level experimentation. This concept has not been widely accepted in the modeling community. The development of this model represents a "first step" in the process of developing a model that will function effectively as a management decision tool that can be integrated into an adaptive management policy.

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Appendix. Parameters and variables

Drivers

Symbol	Description	Units	Range
FMBS	First Month of Breeding Season	Rank	1,2,3...12
PPT	Historical Mean Precipitation	mm year^{-1}	270–700
SC	Soil Characteristics	Unit-less	−1.0–1.0
SR	Stocking Rate	ha (animal-unit-year)$^{-1}$	2–100

State variables

Symbol	Description	Units	Initial value
ANPP	Above Ground Net Primary Production	DM-kg ha^{-1} year^{-1}	RPPT×PUE×RC
BCS	Body Condition Score	Unit-less	7
DSC	Dry Standing Crop	DM-kg ha^{-1}	ANPP×0.56
GSC	Green Standing Crop	DM-kg ha^{-1}	ANPP×0.14
RC	Range Condition	Unit-less	1
RPPT	Random Precipitation	mm year^{-1}	NORMAL(PPT,SD)

Auxiliary variables

Symbol	Description	Units
D	Decomposition Index	Proportion
DNEm	Net Energy for Maintenance in Diet	mcal kg^{-1}
DSCC	Dry Standing Crop Consumed by Cattle	DM-kg ha^{-1} $month^{-1}$
DSCD	Dry Standing Crop Decomposed	DM-kg ha^{-1} $month^{-1}$
DSCT	Dry Standing Crop Trampled by Cattle	DM-kg ha^{-1} $month^{-1}$
F	Frost Index	Proportion
GE	Grazing Efficiency	%
GFD	Green Forage in Diet	Proportion
GI	Growth Index	Proportion
GSCC	Green Standing Crop Consumed by Cattle	DM-kg ha^{-1} $month^{-1}$
GSCF	Green Standing Crop Frosted	DM-kg ha^{-1} $month^{-1}$
GSCS	Green Standing Crop Senescent	DM-kg ha^{-1} $month^{-1}$
GSCT	Green Standing Crop Trampled by Cattle	DM-kg ha^{-1} $month^{-1}$
HGF	Harvestability of Green Forage	Proportion
IRC	Intake Restriction Coefficient	Proportion
Kmh	Harvestability Threshold	TSC, DM-kg ha^{-1}
Kms	Selectivity Threshold	GSC, DM-kg ha^{-1}
MNPP	Monthly Net Primary Production	DM-kg ha^{-1} $month^{-1}$
PGF	Preference of Green Forage	Proportion
PREGNANCY	Pregnancy Rate	%
PUE	Precipitation Use Efficiency	DM-kg ha^{-1} mm^{-1}
PVI	Potential Voluntary Intake	DM-kg $head^{-1}$ day^{-1}
PW	Coefficient Related to BCS	Proportion
RI	Restricted Intake	DM-kg $head^{-1}$ day^{-1}
S	Senescence Index	Proportion
SBW	Shrunk Body Weight	kg $head^{-1}$
SD_1	Stocking Density	Animal-units ha^{-1} day^{-1}
UE	Utilization Effect	Unit-less

Constants[a]

Description	Units	Value
Bred Effect	Unit-less	1
Expected Calf Birth Weight	kg	39
Milk Fat Composition	%	4
Mature Weight at BCS 5	kg $head^{-1}$	450
Peak Milk Yield	kg day^{-1}	8
Milk Solids Not Fat Composition	%	8.3
Terrain (1 = plain; 2 = hilly)	Unit-less	1

[a] These constants do not appear in the text, but are required to parameterize the equations taken from NRC (2000).

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