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Agricultural Systems 88 (2006) 316–331
AGRICULTURAL SYSTEMS
www.elsevier.com/locate/agsy

Use of irrigated pastures in semi-arid grazinglands: A dynamic model for stocking rate decisions

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Received 29 March 2004; received in revised form 3 June 2005; accepted 10 June 2005

Abstract

We present a simple simulation model as an aid to conventional expensive field experimentation and as a decision support system tool for animal production in irrigated pastures within semi-arid grazinglands. We also demonstrate and discuss the integration of results from conventional field experiments within the context of simulation models. We first develop a spreadsheet to estimate animal production under different stocking rates and pasture characteristics, and then incorporate functions from the spreadsheet and from the literature into a dynamic simulation model. The spreadsheet, which is programmed in EXCEL, is a static, deterministic series of calculations that estimates weight gain of grazing animals under different stocking rates and pasture conditions based on decision rules and functions reported by NRC and MAFF. The simulation model, which is programmed in STELLA® Research 6.0 for use on a personal computer, is dynamic and stochastic.

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0308-521X/$ - see front matter
doi:10.1016/j.agsy.2005.06.019

Simulation results were close to observed values for northern Mexico with regard to annual yield of dry standing crop (21,434 vs. 23,637 kg ha^{-1}), dry matter digestibility (67–78% vs. 70–74%), and optimum stocking rate as live weight (892–2567 vs. 2250 kg ha^{-1}). Simulation results indicated the highest optimum stocking rate was 2567 ± 62 kg ha^{-1} in July and the lowest was 892 ± 106 kg; ha^{-1} in January. The highest daily gain per head was 1.144 ± 0.006 kg in February and the lowest was 0.480 ± 0.052 kg in July. Daily forage allowance for the optimum stocking rate varied during the year from 4.05 ± 0.053 in July to 4.84 ± 0.008% of live weight in January. Producers should maintain a herd size that allows maintenance of the optimum stocking rate during months of low growth and, during months of high growth, should graze only the area required to cover the recommended forage allowance, and cut the rest of the forage.

Keywords: Models; Simulation; Stocking rate; Live weight gain; Irrigated pastures

1. Introduction

Livestock husbandry in many parts of the world consists primarily of extensive cow–calf systems based on the use of semi-arid rangelands. In some regions, such as northern Mexico (250–400 mm mean annual precipitation), for example, there is growing interest in the use of irrigated pastures in which to fatten weaned calves before sending them to feedlots; currently weaned calves produced in northern Mexico are sold for fattening in the USA. The area of irrigated perennial pastures in Mexico grew by 76% (82,000–144,000 ha) from 1990 to 2002 (Améndola et al., 2005). Because of the high cost of production, profitable exploitation of irrigated pastures requires a system of forage utilization that maximizes animal production under variable pasture conditions. Decisions concerning stocking rate, which determines grazing pressure, are among the most important because of the close relationship between growth of individual animals and animal production per hectare. Several authors have suggested a negative exponential relationship between individual weight gain and stocking rate (Mott, 1960; Harlan, 1958), with the form of the curve explained by the fact that individual animals can consume to satiation at lower stocking rates but intake and diet quality become limiting as stocking rate increases (Petersen et al., 1965; Owen and Ridgman, 1968). Other authors have suggested a negative linear relationship between individual weight gain and stocking rate (Riewe, 1961; Cowlishaw, 1969), which seems consistent with experimental results obtained in several different types of irrigated pastures under various environmental conditions (Jones and Sandland, 1974). Estimation of the optimum stocking rate (stocking rate producing the maximum live weight gain per hectare) is further complicated by the effects of relative forage availability (Hart, 1972; Duble et al., 1971; Adjei et al., 1980; Conrad et al., 1981; Guerrero et al., 1984) and digestibility (Duble et al., 1971; Guerrero et al., 1984) on individual weight gain.

There are various complex simulation models that have been developed to aid in making stocking rate decisions (Dix and Biedleman, 1969; Wight and Skiles, 1987;

Donnelly et al., 1997; Freer et al., 1997; Loewer, 1998; Carlson and Thurow, 1992). Although the ecological complexity of these models is scientifically interesting, the lack of adequate data bases to parameterize them (data requirements may include items such as canopy height, leaf area index, rooting depth, and soil water content) and the complexity of their output (which may include items such as leaf water storage, water stress, growth, and turnover) have limited their application in grazinglands management. The objective of our work has been to develop simple models (e.g., Diaz-Solis et al., 2003) that both regional managers and individual producers can parameterize based on readily available information, and that produce output that is both understandable and useful to managers.

In this paper, we present a simple systems simulation model as a decision support tool for improving animal production in semi-arid grazinglands via use of irrigated pastures. Optimum stocking rate recommendations have been made for irrigated pastures in both temperate and tropical regions of Mexico based on a series of field experiments conducted between 1970 and 1985 (Diaz and Regla, 1981; Peñuñuri et al., 1983). However, these recommendations consist of a single value (number of animals or total live weight per hectare), without reference to season of the year or stage of forage development. Additional information on stocking rates for irrigated pastures has been produced by several Mexican Universities and centers of investigation, but, to our knowledge, this information has not been used within a dynamic systems modeling framework. Here, we compare simulated and empirical results for pastures of perennial cool season grasses with alfalfa and low fertilization in the southern part of the Mexican state of Coahuila. We also demonstrate the integration of results from conventional field experiments within the context of simulation models and discuss the possibility of using simulation to reduce the cost of experimental research. More specifically, we first developed a spreadsheet to estimate animal production under different stocking rates and pasture conditions, and then incorporated functions derived from results of the spreadsheet and published literature into a dynamic simulation model to evaluate different stocking rate scenarios.

2. Materials and methods

We developed the model for irrigated pastures with a mixture of grasses (*Dactylis glomerata*, *Festuca arundinacea*, *Lolium perenne*), and alfalfa (*Medicago sativa*) in the region near Buenavista, Saltillo, Coahuila, Mexico (25°28′N, 100°57′W and 1743 m above sea level). Since these pastures are irrigated, we assumed that soil moisture was not limiting and that air temperature was the variable that controled forage production and nutritive value. Mean monthly temperatures (and the associated standard deviations) based on 30 years of data (1968–1998) from the Buenavista's climatatological station were: 11.41 (4.33), 13.31 (4.12), 15.44 (4.27), 18.20 (3.84), 20.31 (3.06), 21.18 (2.66), 20.68 (1.97), 20.18 (1.99), 18.47 (2.66), 16.63 (3.28), 14.05 (4.33), and 12.64 (4.27) °C for January through December, respectively (TEMP in Fig. 1).

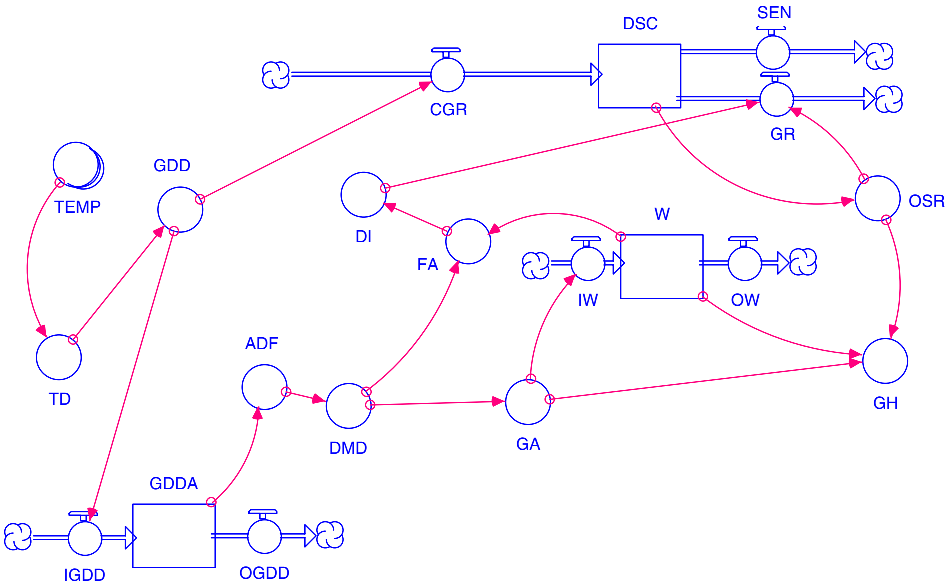

Fig. 1. Diagrammatic representation of the relationships among the principal components in the dynamic simulation model.

2.1. Description of the spreadsheet

The spreadsheet, which is programmed in EXCEL, is a static, deterministic series of calculations that estimates weight gain of grazing animals under different stocking rates (SR) and pasture conditions based on decision rules and functions reported by NRC (1984) and MAFF (1984). We parameterized the spreadsheet to calculate weight gain per animal (GA, kg animal^{-1} day^{-1}) and per hectare (GH, kg ha^{-1} day^{-1}) at stocking rates ranging from 2 to 30 animals ha^{-1} under a wide range of pasture conditions indicated by: mean LW of grazing animals (W, kg), dry standing crop (DSC, kg ha^{-1}), and dry matter digestibility (DMD, %). (Table 1 contains a list of symbols used in the text, including description, units of measure, and equation number where first presented.)

The spreadsheet first calculates voluntary intake of dry matter (VI, kg animal^{-1} day^{-1}) via the equation of Fox (NRC, 1987):

$$\mathrm{VI} = ((W^{0.75}) * (19.5 + 54.5 * \mathrm{NEm}))/1000, \tag{1}$$

where W (kg) is mean LW of animals and NEm (Mcal kg^{-1}) is net energy for maintenance of the forage.

$$\mathrm{NEm} = (1.37 * \mathrm{ME}) - (0.138 * \mathrm{ME}^2) + (0.0105 * \mathrm{ME}^3) - 1.12. \tag{2}$$

NEm and net energy for gain of the forage (NEg, Mcal kg^{-1}) are based on metabolizable energy (ME) (NRC, 1984):

Table 1
List of symbols used in the text, including description, units of measure, and equation number where first presented

Symbol	Description	Units	Eq. no.
ADF	Acid detergent fiber	%	(10)
CGR	Crop growth rate	kg DM ha^{-1} day^{-1}	(8)
DI	Daily intake	% of W	(12)
DM	Dry matter	kg	NA
DMD	Dry matter digestibility	%	(11)
DMg	Dry matter for gain	kg $animal^{-1}$ day^{-1}	(7)
DMm	Dry matter for maintenance	kg $animal^{-1}$ day^{-1}	(6)
DOMD	Digestible organic matter in dry matter	%	(4)
DSC	Dry standing crop	kg ha^{-1}	(8)
FA	Forage allowable per day	% of *W*	(15)
GA	Gain per animal	kg $animal^{-1}$ day^{-1}	(7)
GDD	Growth degree days	Unit-less	(9)
GDDA	Cumulative growth degree days	Unit-less	(10)
GH	Gain per hectare	kg ha^{-1} day^{-1}	(12)
GR	Grazing forage losses	kg DM ha^{-1} day^{-1}	(8)
LAU	Losses per animal unit	kg $animal^{-1}$ day^{-1}	NA
ME	Metabolizable energy	Mcal $(kg\ DM)^{-1}$	(2)
NEg	Net energy for gain	Mcal $(kg\ DM)^{-1}$	(3)
NEm	Net energy for maintenance	Mcal $(kg\ DM)^{-1}$	(2)
OSR	Optimum stocking rate	kg LW ha^{-1}	(12)
SEN	Senescence	kg DM ha^{-1} day^{-1}	(8)
SR	Stocking rate	Animals ha^{-1}	NA
TB	Base temperature	°C	NA
TD	Mean daily temperature	°C	NA
TL	Trampling losses	kg $herd^{-1}$ day^{-1}	(13)
VI	Voluntary intake	kg DM $animal^{-1}$ day^{-1}	(1)
W	LW per animal	kg $animal^{-1}$	(12)

$$NEg = (1.42 * ME) - (0.174 * ME^2) + (0.0122 * ME^3) - 1.65. \quad (3)$$

ME (Mcal kg^{-1}) is calculated based on digestible organic matter in dry matter (DOMD, %) (MAFF, 1984):

$$ME = (DOMD * 0.15) * 0.2389, \quad (4)$$

where the last constant converts MJ kg^{-1} to Mcal kg^{-1}.

The relationship between DOMD (%) and dry matter digestibility (DMD, %) was taken from MAFF (1984):

$$DOMD = -4.8 + 0.98 * DMD. \quad (5)$$

The spreadsheet then calculates forage availability per animal per day for different stocking rates. We assumed that, with intensive rational grazing, 40% of forage is unavailable (residual forage), as observed by Morales (1999) in an experiment with similar pastures and environment. Daily intake (DI) per animal was calculated with the following decision rule: when available forage was greater than daily voluntary intake (VI), daily intake was equal to voluntary intake, when available forage was less than daily voluntary intake, daily intake was equal to forage available per animal.

NEm of the forage was used to estimate the amount of dry matter required for maintenance (DMm, kg DM animal^{-1} day^{-1}) according to NRC (1984):

$$\mathrm{DMm} = (0.077 * W^{0.75})/\mathrm{NEm}. \tag{6}$$

The difference between dry matter required for maintenance and dry matter intake was considered as dry matter available for weight gain (DMg, kg DM animal^{-1} day^{-1}). Thus, daily weight gain per animal (GA, kg animal^{-1} day^{-1}) was calculated as:

$$\mathrm{GA} = ((\mathrm{DMg} * \mathrm{ENg})^{0.9116}) * 13.91 * (W^{-0.6837}); \quad (\mathrm{NRC, 1984}). \tag{7}$$

The gain per hectare per day (GH) was equal to GA * SR.

We used the spreadsheet to estimate: (1) optimal (biological) stocking rate (OSR; stocking rate which maximized weight gain per hectare); (2) forage allowance at the optimum stocking rate (FA); (3) daily intake per animal at optimum stocking rate (DI); and (4) GA for each of the 150 combinations of the following values of the 3 independent variables: $W = 150$, 200, 250, 300, and 350 kg; DSC = 1000, 1500, 2000, 2500, 3000, and 3500 kg ha^{-1} month^{-1}; and DMD = 61%, 66%, 71%, 76%, and 81% using linear regression. To estimate the effect of selectivity on weight gain per animal, we assumed a negative linear relationship between stocking rate and weight gain per animal, even at stocking rates lower than the optimum, since diet quality should improve with increasing forage allowance due to higher opportunity for diet selection (Riewe, 1961; Cowlishaw, 1969; Jones and Sandland, 1974). For DMD values of 65%, 70%, and 75%, we calculated GA at stocking rates below the optimum by linear extrapolation. Then the calculated GA was related to daily forage allowance.

2.2. Description of the simulation model

The simulation model, programmed in STELLA® Research 6.0 (High Performance Systems, Inc., Hanover, New Hampshire) for use on a personal computer, is formulated as a stochastic compartmental model based on difference equations with a 1-day time step ($\Delta t = 1$ day) (Fig. 1). The model represents a rotational grazing system with 1 day of grazing and 30 days of regrowth.

We calculated dry standing crop dynamics (DSC; kg DM ha^{-1}) as:

$$\mathrm{DSC}(t+1) = \mathrm{DSC}(t) + (\mathrm{CGR} - \mathrm{GR} - \mathrm{SEN}) * \Delta t, \tag{8}$$

where CGR represents crop growth rate (kg DM ha^{-1} day^{-1}) and was calculated based on regional data from an experiment of more than 2 years with pastures of perennial cool season grasses and alfalfa (Gutiérrez, 1991):

$$\mathrm{CGR} = -17.835 + 6.88 * \mathrm{GDD}; \quad R^2 = 0.64, \tag{9}$$

where GDD represents growing degree-day.

GDD = TD − TB when TD is greater than TB, when TD is less than or equal to TB, then GDD = 0. TD represents the mean daily temperature in °C, which is drawn randomly from a normal distribution of temperatures for the given day of the year based on 30 years (1968–1998) of data from the climatological station near Buenavista, Saltillo, Coahuila (25°28′N, 100°57′W; 1743 m above sea level) and TB is base temperature for growth, which equals 4 °C (Kiniry et al., 1991). We calculate GR (grazing losses) using Eq. (13) below, and losses due to senescence (SEN) as 80% of residual forage.

We calculate the nutritive value of forage as a function of acid detergent fiber (ADF; %) based on GDD accumulated during regrowth (GDDA). Morales (1999) has established this relationship for the type of pastures we are simulating:

$$\mathrm{ADF} = 37.44 - 0.063 * \mathrm{GDDA} + 0.00013 * \mathrm{GDDA}^2; \quad R^2 = 0.27. \tag{10}$$

We calculate dry matter digestibility (DMD; %) based on ADF, using an equation also obtained from data for the type of pastures we are simulating (Diaz, 1995):

$$\mathrm{DMD} = 110.45 - 1.08 * \mathrm{ADF}; \quad R^2 = 0.42. \tag{11}$$

We then calculate optimum stocking rate (OSR; kg per hectare), daily forage allowance (FA; % of W), daily intake (DI; % of W), and daily weight gain per animal (GA; kg) using Eqs. (11)–(14), respectively.

We simulate mean W of groups of animals from 200 to 320 kg. When a group of animals reaches a mean weight of 320 kg, we introduce a new group of animals weighing 200 kg.

We calculate daily LW gain per hectare (GH; kg) as:

$$\mathrm{GH} = \mathrm{GA} * (\mathrm{OSR}/W). \tag{12}$$

We calculate grazing losses from DSC, which include forage intake, trampling loss, and loss due to deposition of feces (TL), as:

$$\mathrm{GR} = (\mathrm{DI}/100 * \mathrm{OSR} * 30) + \mathrm{TL}, \tag{13}$$

where TL = OSR/450 * LAU
where LAU represents loss per animal day^{-1}, which is a linear function of the amount of dry standing crop (DSC): LAU = 0 when DSC = 0 and LAU = 3 kg when DSC = 4000 kg DM ha^{-1}.

2.3. Evaluation of the simulation model

We evaluated performance of the simulation model by comparing model predictions of annual yield of dry standing crop and monthly dry standing crop to field data collected from irrigated pastures of alfalfa with grasses in Rancho el Aguatoche (25°06′52″ latitude N, 100°50′07″ longitude W, elevation 1855 m) (Morales, 1999). This site is colder than the site for which the model was initially parameterized (Buenavista), thus, we reparameterized the model using mean monthly temperatures recorded in el Aguatoche during the study period and ran the model in a deterministic form. We also compared model predictions of forage allowance (Hodgson, 1991; Butler et al., 2003 and Gonzáles et al., 2004), digestibility (Diaz, 1995), and optimum stocking rate (Diaz and Regla, 1981; Peñuñuri et al., 1983; Rouquette, 1993).

3. Results

3.1. Spreadsheet

Spreadsheet calculations for weight gain per animal (GA) and per hectare (GH) at different stocking rates and combinations of forage availability (DSC) and digestibility (DMD) indicated that optimum stocking rates ranged from 4 to 10 animals ha^{-1} (Fig. 2). Weight gain per head was negatively linearly related to stocking rate at stocking rates above the optimum. Stocking rate was primarily a function of forage availability. Weight gain per animal was a function of forage digestibility and daily forage allowance (FA) (Fig. 3).

Spreadsheet calculations yielded the following equations for optimal stocking rate (OSR, kg LW ha^{-1}), daily forage allowance at the optimum stocking rate (FA, % of W), daily intake (DI, % of W), and daily weight gain per animal (GA, kg $animal^{-1}$):

$$\mathrm{OSR} = -10.44 + 0.7843 * \mathrm{DSC}\ (\mathrm{kg\,ha^{-1}}); \quad R^2 = 0.86, \tag{14}$$

$$\mathrm{FA} = 1.016 + 0.06 * \mathrm{DMD}\ (\%) - 0.00427 * W(\mathrm{kg}); \quad R^2 = 0.90, \tag{15}$$

$$\mathrm{DI} = 0.0235 + 0.577 * \mathrm{FA}\ (\%); \quad R^2 = 0.83, \tag{16}$$

$$\mathrm{GA} = -3.5417 + 0.06 * \mathrm{DMD}\ (\%); \quad R^2 = 0.98. \tag{17}$$

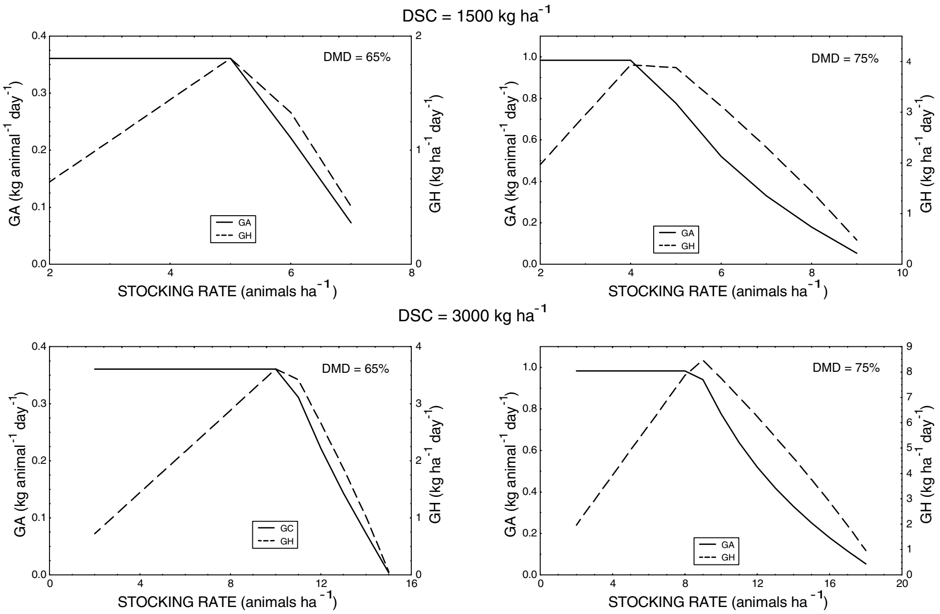

Fig. 2. Spreadsheet predictions of weight gain per animal (GA) and per hectare (GH) at different stocking rates and combinations of dry standing crop (DSC) and digestibility (DMD). Animal weight was held constant at $W = 250$ kg.

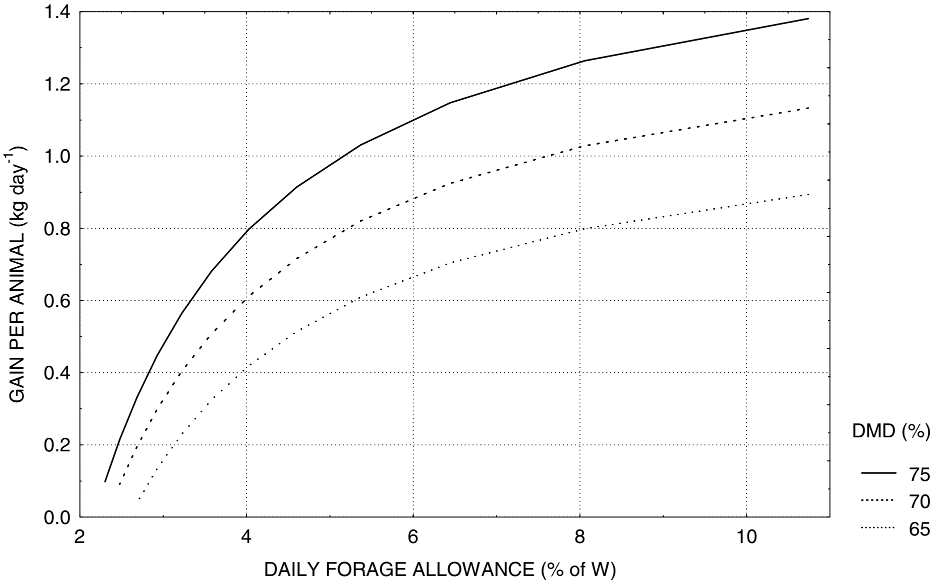

Fig. 3. Spreadsheet predictions of the relationship between daily forage allowance (FA) and weight gain per animal (GA) at different levels of dry matter digestibility (DMD).

3.2. Evaluation of the simulation model

Simulated annual yield of dry standing crop was similar to the annual yield observed by Morales (1999) at Rancho el Aguatoche (21,434 and 23,637 kg ha^{-1}, respectively); simulated and observed monthly dry standing crop also were similar (Fig. 4). Dry matter digestibilities simulated for Buenavista were similar to those observed in the state of Chihuahua, Mexico for various mixtures of temperate perennial species (near 70%) (Diaz, 1995). The simulated optimum stocking rate varied from 892 to 2567 kg LW ha^{-1}, which was similar to the recommendation for irrigated pastures of Italian rye grass in Sonora, Mexico (2250 kg LW ha^{-1}) (Peñuñuri et al., 1983). In pastures of low nutritive value, such as bermudagrass (*Cynodon dactylon*) in the southwest US grazed during summer, optimum stocking rate was higher and ranged from 1007 to 3588 kg LW ha^{-1} (Rouquette, 1993). In northwest Mexico, in irrigated bermudagrass pastures fertilized with N, optimum stocking rate was of 3444 kg LW ha^{-1} (Lizárraga et al., 1995). Bermudagrass is a tropical species of low to moderate nutritive value, so weight gains ranged only from 0.4 to 0.6 kg animal^{-1} day^{-1}.

3.3. Simulation model application

Simulated seasonal dynamics of mean: (1) dry standing crop (DSC, kg ha^{-1}); (2) dry matter digestibility (DMD, %); (3) optimal stocking rate (OSR, kg LW ha^{-1});

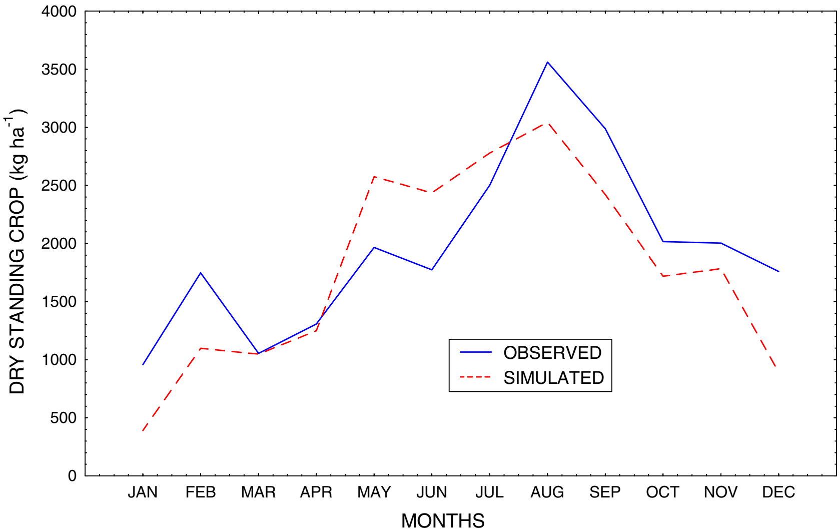

Fig. 4. Comparison of simulated and observed monthly dry standing crop (DSC) (Morales, 1999).

and (4) mean animal LW (*W*, kg) of 2 groups of animals, based on 100 replicate stochastic simulations, are presented in Fig. 5. Forage production and forage quality followed inverse trends. During spring, OSR and mean weight per animal increased together. However, during the fall, OSR decreased as weight per animal was increasing. This will make it more difficult to manage stocking rates.

Mean monthly values for cumulative growth degree-days (GDDA), daily forage allowance (FA, % of *W*), daily intake (DI, % of *W*), daily LW gain per animal (GA, kg), and daily LW gain per hectare (GH, kg) are summarized in Table 2. The cumulative growth degree-days (GDDA) for each regrowth period was lowest in January (224.18) and highest in July (517.02). Forage allowance at the optimum stocking rate varied from 4.05% in July to 4.84% in January. Daily intake of dry matter ranged from 2.36% of LW in July to 2.82% in January. Daily weight gain per animal ranged from 0.480 kg in July to 1.144 kg in February.

Forage allowance was relatively constant through out the year, but gain per animal closely tracked forage digestibility, being highest during the cool months and lowest in the warm months. Gains during the summer were similar to those reported by Rouquette (1993). Gain per animal tended to compensate for changes in OSR, resulting in relatively constant gain ha^{-1} da^{-1} across months.

Dry standing crop after 30 days of regrowth was highest in July (3286 ± 79 kg ha^{-1}) and lowest in January (1150 ± 135 kg ha^{-1}) (Fig. 5(a)). Temperature had an inverse effect on dry matter digestibility; DMD was $67.0 \pm 0.9\%$ in July and $78.1 \pm 0.1\%$ in February (Fig. 5(b)). Optimum stocking rate was 2567 ± 62 kg LW ha^{-1} in July and 892 ± 106 kg ha^{-1} in January. Thus, optimum stocking rate was more related to the quantity of dry standing crop than to dry

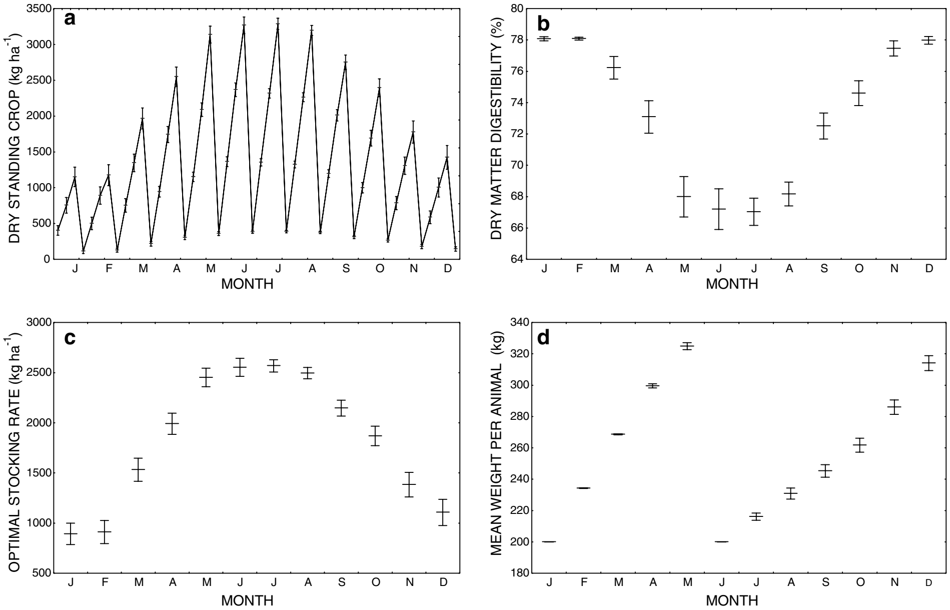

Fig. 5. Simulated seasonal dynamics of mean: (a) dry standing crop (DSC); (b) dry matter digestibility (DMD); (c) optimal stocking rate (OSR); and (d) mean weight per animal (W) of 2 groups of animals. In (a), based on 100 replicate stochastic simulations, standard deviations are presented for days 10, 20, and 30 of each regrowth period.

Table 2
Monthly values (mean ± 1 standard deviation, $n = 100$) for cumulative growth degree-day (GDDA), and the corresponding values to optimum stocking rate for daily forage allowance (FA), daily intake (DI), daily weight gain per animal (GA), and daily weight gain per hectare (GH)

Month	GDDA	FA (% of *W*)	DI (% of *W*)	GA (kg animal^{-1} day^{-1})	GH (kg ha^{-1} day^{-1})
January	224.18 ± 21.63	4.84 ± 0.009	2.82 ± 0.004	1.143 ± 0.008	5.10 ± 0.63
February	228.31 ± 22.04	4.69 ± 0.005	2.73 ± 0.005	1.144 ± 0.006	4.45 ± 0.57
March	353.03 ± 21.67	4.44 ± 0.044	2.58 ± 0.024	1.030 ± 0.043	5.87 ± 0.20
April	425.85 ± 19.47	4.12 ± 0.062	2.40 ± 0.036	0.844 ± 0.062	5.58 ± 0.14
May	504.37 ± 16.90	4.24 ± 0.078	2.47 ± 0.045	0.538 ± 0.077	6.56 ± 0.71
June	514.61 ± 16.33	4.12 ± 0.077	2.40 ± 0.045	0.491 ± 0.078	5.76 ± 0.73
July	517.02 ± 10.90	4.05 ± 0.053	2.36 ± 0.030	0.480 ± 0.052	5.33 ± 0.46
August	502.45 ± 10.09	4.06 ± 0.047	2.36 ± 0.027	0.549 ± 0.046	5.57 ± 0.34
September	436.70 ± 14.73	4.24 ± 0.054	2.47 ± 0.031	0.809 ± 0.050	6.62 ± 0.21
October	395.28 ± 17.83	4.27 ± 0.053	2.49 ± 0.031	0.935 ± 0.047	6.09 ± 0.12
November	305.28 ± 23.09	4.70 ± 0.193	2.73 ± 0.111	1.105 ± 0.029	7.03 ± 1.25
December	265.46 ± 25.32	4.73 ± 0.062	2.70 ± 0.036	1.137 ± 0.015	5.60 ± 0.74

matter digestibility (Fig. 5(c)). Growth rate for the two groups of animals differed greatly; the first group reached 325 kg in 4 months (January–April) whereas the second group needed 6 months (May–October) to reach 315 kg (Fig. 5(c)).

4. Discussion

Results of the spreadsheet should be more accurate over a wider range of climates than those of the dynamic model, because, under the temperature range of Buenavista, the relationship between temperature and crop growth rate (CGR) was linear. However, over a wider range of temperatures, crop growth rate (CGR) and temperature have a non-linear relationship. Thus, the dynamic model should be better in regions similar to Buenavista, with a range of mean monthly temperatures between 11 and 22 °C for coldest and warmest months, respectively.

Stocking rate was affected more by the amount of forage and weight gain per animal was affected more by dry matter digestibility (Fig. 2). This is because voluntary intake was positively correlated with forage digestibility. Thus, within the range of DMD studied, the best strategy when forage digestibility was high was to maintain low stocking rates with high weight gain per animal; whereas, when forage digestibility was low but availability was high, the best strategy was to maintain high stocking rates with lower weight gain per animal. These trends are supported by Rouquette (1993), who found higher optimum stocking rates (1007–3588 kg LW ha^{-1}, our results indicated 892–2567 kg LW ha^{-1}) for lower quality pastures (bermudagrass, *Cynodon dactylon*).

Spreadsheet calculations were similar to those obtained by other investigators (Riewe, 1961; Petersen et al., 1965; Owen and Ridgman, 1968); weight gain per animal did not increase as stocking rates were reduced below the optimum level. Other models assume that weight gain per animal is higher at stocking rates below the optimum because forage availability is higher and animals can be more selective in their diet choices (Jones and Sandland, 1974). Animals should reach a threshold in terms of their maximum capacity for diet selectivity such that they can no longer increase weight gain as forage allowance increases. According to equations from Jones and Sandland (1974), with a daily forage allowance greater than 7% of LW and a dry matter digestibility of 75%, daily weight gain per animal reaches values greater than 1.2 kg (Fig. 3). This is unlikely in irrigated pastures, reinforcing the idea that there may be a threshold of diet selectivity which was not considered in their calculations. On the other hand, according to Jones and Sandland (1974), for forages with low dry matter digestibility (60%, 55%, 50%), as is typical in irrigated tropical pastures with grasses, daily forage allowance should be 8–10% of LW to achieve acceptable daily weight gains (0.4–0.6 kg) (Fig. 3). This agrees with reports for irrigated pastures of bermudagrass (Guerrero et al., 1984), and is reasonable because, with forage of low nutritive value, it is necessary to facilitate selection of diets of greater nutritive value and increased voluntary intake resulting in increased daily weight gain.

Temperature was positively correlated with the accumulation of dry standing crop and negatively correlated with dry matter digestibility, which is reasonable because accumulation of degree days drives the phenological development of plants and digestibility of plants declines as they mature (Gill et al., 1980; Onstad and Fick, 1983; Kiniry et al., 1991).

Daily weight gain was a function of dry matter digestibility since the effect of forage availability and mean animal weight were minimized by simulating for the optimum stocking rate. The high weight gain per hectare in November resulted from a combination of high forage availability and digestibility, which maximized animal production.

Optimum stocking rate varied from 892 to 2567 kg LW ha^{-1}. Optimum stocking rate recommendations based on experiments conducted in intensively managed irrigated pastures in Mexico consist of a single value calculated from average conditions during the production cycle. The recommendation for irrigated pastures of bermudagrass cross 1 with high fertilization is 2000 kg LW ha^{-1} (Diaz and Regla, 1981). However, conditions in this type of pasture vary seasonally and, hence, the optimum stocking rate also varies. The optimum stocking rate for irrigated pastures depends primarily on the quantity and nutritive value of the available forage, both of which vary seasonally. Thus, one advantage of using a simulation model is that optimum stocking rates can be estimated month by month based on changing pasture conditions. Such estimations based on conventional field experiments would be prohibitively expensive.

Daily forage allowance at the optimum stocking rate was between 4% and 5% of LW, which agrees with the recommendation to allow twice the expected intake in irrigated temperate pastures (Hodgson, 1991). Butler et al. (2003) with Holstein–Friesian cows in temperate pastures, reported that the optimal forage allowance for milk production is from 4% to 5%. We can expect a higher forage allowance because more nutrients are required for milk production than for animal growth, however, these authors reported forage allowance as the forage 7 cm above ground, so considering forage allowance from ground level as we did, the values reported by Butler et al. must be higher. Gonzáles et al. (2004) reported that forage allowance for growing animals in temperate pastures should be higher than 4% of animal mass.

Average daily dry matter intake estimated by the model was 2.54% of W. We obtained a positive linear relationship between forage allowance and intake because during model development we only considered forage allowance at the optimum stocking rate. More generally, intake varies logarithmically along a gradient of forage allowances (Duble et al., 1971; Dougherty et al., 1992; Rocha, 1999). Considering fixed values for forage allowances, other investigators have reported values for intake similar to those estimated with our model (MAFF, 1984; Dougherty et al., 1992; Rocha, 1999; Gonzáles, 1999). In Fig. 3, daily weight gain with the daily forage allowance of 4.5% suggested by our model, is close to the 0.5, 0.7, and 0.9 kg animal^{-1} day^{-1} reported for irrigated pastures with dry matter digestibilities of 65%, 70%, and 75%, respectively, which is common from tropical to temperate well-managed pastures. From several experiments with bermudagrass pastures, Rouquette (1993) concluded that the forage dry matter allowance required to maximize gain per animal was 2–4.5 times greater than the amount required for maintenance; our model reports similar values of 1.96–5.1 times the amount required for maintenance.

The optimum forage allowance varied less seasonally (4.05–4.84%) and, hence, could be used for management of irrigated commercial pastures. This does not imply that a producer should buy or sell animals each month, but, rather, that he/she should have an amount of pasture and a herd size that will allow maintenance of the optimum stocking rate during those months of low growth and to graze the entire pasture during these months. In months of high growth, the producer should graze the area required to cover the recommended forage allowance and conserve the forage in the rest of the pasture.

5. Conclusions

The integration of information generated from isolated field experiments into simulation models contributes to a more dynamic understanding of the system under study. Simulation models provide producers with a management tool to integrate specific information about their ranches within a broader, more useful, context. Results of simulation studies help researchers identify and prioritize specific field experiments that will provide data for improving the usefulness of the model, thus making more productive and wiser use of the resources dedicated to field investigation.

Both the spreadsheet and the simulation model presented in this paper produced results similar to those observed in field studies. This model has potential to be used as a management tool to aid decisions regarding not only stocking rates, but also supplemental feeding and the harvest of excess forage. The model can be parameterized based on readily available information and produces output that is both understandable and useful to managers. It should be relatively simple to adapt the model to other temperate irrigated pastures based on information on soil type and temperature. Future research on simulation models for irrigated pastures in semi-arid grazinglands should emphasize representation of a threshold for forage selectivity.

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