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Validation of SPUR2.4 rangeland simulation model using a cow-calf field experiment

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Abstract

SPUR (Simulation of Production and Utilization of Rangelands) is a grassland ecosystem simulation model. SPUR2.4 output was compared with 29 years of cow-calf data from a field experiment conducted in north-central Texas, USA. Simulated primary productivity for C_4 shortgrass was good, adequate for C_4 mid-grass and live C_3 wintergrass but inadequate for total wintergrass. The productivity of C_3 annual grass predicted by the model was of the same order of magnitude as productivity measured in the field and appears to be adequate in terms of predicting secondary production. Between-season herbage standing crop and long-term persistence were simulated adequately for individual soils but not for areas containing more than one soil series. The model gave accurate simulations of weaning weight per hectare for both the purebred Hereford and Charolais-cross animals for all grazing treatments and intensities. However, the lack of ability to simulate accurately with more than one soil per grazing unit must be corrected before the model will adequately simulate secondary productivity for landscapes that contain different soil series. © 2001 Published by Elsevier Science Ltd. All rights reserved.

1. Introduction

Rangelands are semi-natural ecosystems manipulated by humans to obtain a productive output, usually with domestic livestock. Natural plant communities support these pastoral enterprises, and native fauna, although modified, co-exist with domestic livestock. Climatic forces control the ecosystem to a far larger extent

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than does management (Harrington et al., 1984). The inherently low productivity of rangelands means that each management area is large. Variability among management units is usually high because they are large and edaphically and topographically heterogeneous. This variability complicates decision-making and the transfer of knowledge gained from research areas.

Modelling is one of the few approaches available to assess the factors affecting primary and secondary productivity at different sites. It can be used to assess the consequences of different site physical properties and levels of inputs or management actions for different land management units, and address these issues at the whole ranch level (Coughenour, 1991; Teague, 1996). In order to be useful as a decision aid, a model must be verified, parameterized, calibrated and validated for a specific set of data from the area where the decision aid is to be used.

SPUR (Simulation of Production and Utilization of Rangelands) was designed to simulate rangeland ecosystem function and predict ecosystem response to changing physical parameters and various management practices (Wight and Skiles, 1987; Baker et al., 1992; Foy, 1993; Carlson and Thurow, 1996). It has the potential to evaluate the environmental and economic impact of different management alternatives at the landscape or whole ranch scale. The output from SPUR can be selected to include estimates of rainfall runoff, soil loss, soil organic-matter content, plant production, forage selected and harvested by livestock and wildlife, animal weight and gain, and net economic return. Once SPUR is calibrated for a particular location, the model can be run to predict the long-term outcome of management strategies and weather sequences and to assess the relative merits of different management strategies or combinations of management practices (Baker et al., 1993; Foy, 1993).

In this paper, SPUR2.4 (Foy et al., 1999) is used to assess whether measurements taken in a rangeland grazing experiment are simulated with sufficient accuracy that the model can be used as the basis for improving management decisions for ranch properties in the same ecoregion and to enhance understanding by assessing the relative merits of different management actions.

2. Methods

2.1. Model description

SPUR is composed of six basic submodels (Fig. 1; see Carlson and Thurow, 1992; Hanson et al., 1992). The climate record provides daily inputs of precipitation, maximum and minimum temperature, solar radiation, and wind run. The hydrology component maintains daily water balance, calculates snow accumulation, snowmelt and sediment transport. The soil module tracks soil moisture by soil layer according to soil series characteristics and soil carbon and nitrogen levels. The plant module tracks carbon and nitrogen flows through various live and dead state variables, and has the potential to simulate competition between species.

In the livestock component, forage intake, diet selection, reproduction and weight gain or loss are simulated. A cow-calf, beef cattle submodel simulates up to 18

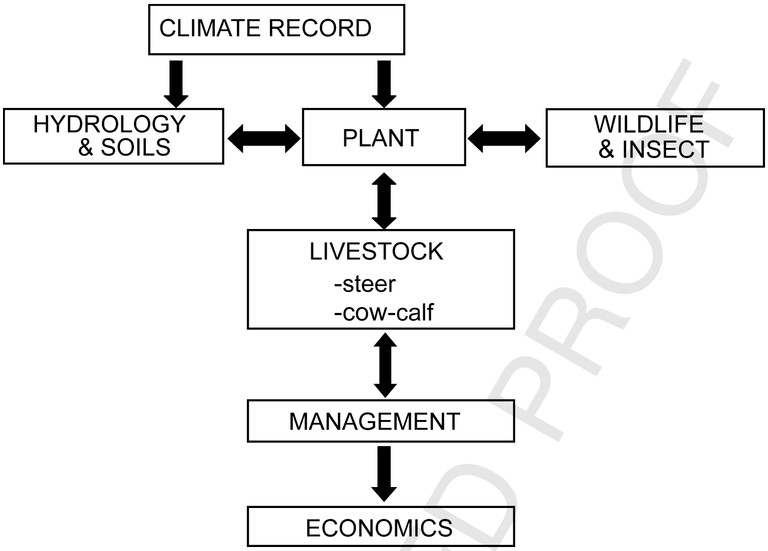

Fig. 1. Modules and linkages within SPUR 2.4.

genetic traits for the life time of each individual in the herd. The wildlife and insect component simulates herbage selection and removal. Populations are simplistically simulated and can be parameterized to fit data on population levels and fluctuations.

Various management options are possible and the economic module is a simple application of cost-benefit analysis.

2.2. Model calibration and validation

As an ecosystem model is used and improved, model development becomes an iterative process of corroborating the model under changing conditions and improving its performance and correlation with known data (Nolan, 1972; Rykiel, 1996). Verification is a demonstration that the modelling formalism is correct (Rykiel, 1996). This procedure is described for earlier versions of the model, SPUR2.3 in Foy (1993) and SPUR91 in Carlson and Thurow (1992). Calibration is the estimation and adjustment of model parameters and constants to improve the agreement between model output and a data set (Rykiel, 1996). Initial calibration of SPUR2.4 was limited to one site and one soil at the Texas Experimental Ranch (TER) and is described in detail in Foy et al. (1999).

Calibration of SPUR2.4 for this exercise was much more complicated and time-consuming than for the single soil series lysimeters (one site and one soil) at the TER (Foy et al., 1999). There were five soil series represented in the plant and animal dataset. Soil series were not equally represented in each of the treatments (Table 1). Initial plant values were assigned to each soil series, based on the data collected. Plant production was calibrated for a weighted mean of each of these five soil series. Soil organic-matter content was kept the same for all soils. In addition, grasshoppers

Table 1
The proportion of each soil series present in different grazing treatments at the Texas Experimental Ranch Throckmorton, Texas

Soil series	Herbage production potential[a] (kg ha^{-1} year^{-1})	Treatment		
		Moderate continuous (%)	Heavy continuous (%)	Deferred rotation (%)
Frio	4000	6	9	9
Leeray	3500	6	24	30
Nuvalde	3100	17	6	37
Throck	2500	56	46	21
Owens	2000	15	15	3

[a] From USDA Soil Conservation Service (1975).

were added and animals were allowed to consume a small proportion of dead wintergrass, as observed in the field. These modifications increased the complexity compared to the one site, one soil calibration reported previously (Foy et al., 1999).

Validation is a demonstration that a model, within its domain of applicability, possesses a satisfactory range of accuracy consistent with the intended application of the model (Rykiel, 1996).

2.3. The field experiment

Forage standing crop and livestock production output from the model were compared with data collected in grazing experiments conducted first by Kothmann et al. (1970, 1978) and then by Heitschmidt et al. (1982a, 1982b, 1985, 1990) at the Texas Experimental Ranch and unpublished field day information from the same venue (Texas Agricultural Experiment Station, 1985). Three treatments are used from these field experiments that were conducted from 1961 to 1989. These treatments were moderate continuous (MC) and heavy continuous (HC) stocking at 7 and 5 ha AUY^{-1}, respectively, and a deferred-rotation (DR) grazing system stocked at 7 ha AUY^{-1}. The DR treatment involved three herds of cows grazing four pastures. Standing crop data were not measured for the DR treatment. The treatment areas had different proportions of each soil series in each treatment (Table 1). Abbreviations used in the text are in the Appendix, Table A1.

The wildlife component of the model was turned off since no wildlife data were available. The grasshopper population dynamics submodel simulates daily dynamics of two types of spring emerging grasshoppers; “grass feeders” that feed exclusively on grass species present and “mixed feeders” that feed on grasses and forbs. Grasshoppers can significantly reduce carrying capacity because they are more competitive grazers than cattle and their demand for forage is likely to be highest when forage production is lowest (Hanson et al., 1992). To simulate grasshopper populations reported in this ecoregion by Parajulee et al. (1997), grasshopper populations were generated using an emergence date of Julian day 130 and initial population levels for grass feeders and mixed feeders of 150 and 300, respectively.

From 1961 to 1978 the treatments were stocked with purebred Hereford cows bred to Hereford bulls. From 1979 to 1989 they were stocked with Hereford×Angus crossbred cows bred to Charolais bulls. Crossbreeding is practiced since it causes heterosis (hybrid vigour) that increases productivity. The amount of heterosis differs according to the breeds involved. Heterosis values from Long (1980) were used to parameterize the genetic portion of the model. Parameter values that were used in the genetic portion of the model are provided in the Appendix, Table A2.

In this environment, dietary protein levels in winter commonly fall below the requirements of pregnant and lactating cows. In the experiment, protein was fed as necessary to overcome this shortfall. The cow herd in the DR treatment was supplemented every winter, but in the MC and HC treatments only the Hereford×Angus crossbred cows were supplemented. In the simulations, supplements were "fed" at the same rates as in the experiment.

The experiment was not designed with the idea of validating a model and the dataset is incomplete for the purposes of conducting a complete validation. Detailed plant data were not available for the entire period and we used the model calibration parameters from the MC treatment to determine if cattle weight gains were accurate even though we could not validate plant growth or herbage availability within the DR treatment. Parameter values used that affect the magnitude and timing of plant growth in the model are in the Appendix, Table A3.

Initially SPUR2.4 was calibrated as tightly as possible to the available soil, hydrology, plant and livestock data for the moderately stocked (MC) treatment. This calibration was not part of the validation process. Once calibration was complete, the model output was compared to the data from the other treatments, HC and DR, using the SAS statistical package means and regression procedures (SAS, 1990).

3. Results and discussion

The range in values in the primary data and the range in variation across years among grasses has been presented in a previous paper (Foy et al., 1999). To illustrate the range in values of the primary livestock data over the experimental period the annual values for calves weaned per 100 cows exposed and weaned calf mass per hectare for each treatment are presented in Fig. 2.

3.1. Plant standing crop

To obtain good estimates of plant growth an accurate estimate of soil water content is necessary. As indicated by Carlson et al. (1995) and Foy et al. (1999) soil water content is estimated reasonably accurately by SPUR2.4. Simulated values for live herbage fell within the standard errors of the field data for both the MC and HC treatments (Fig. 3). However, for live plus dead herbage, simulated values fell within

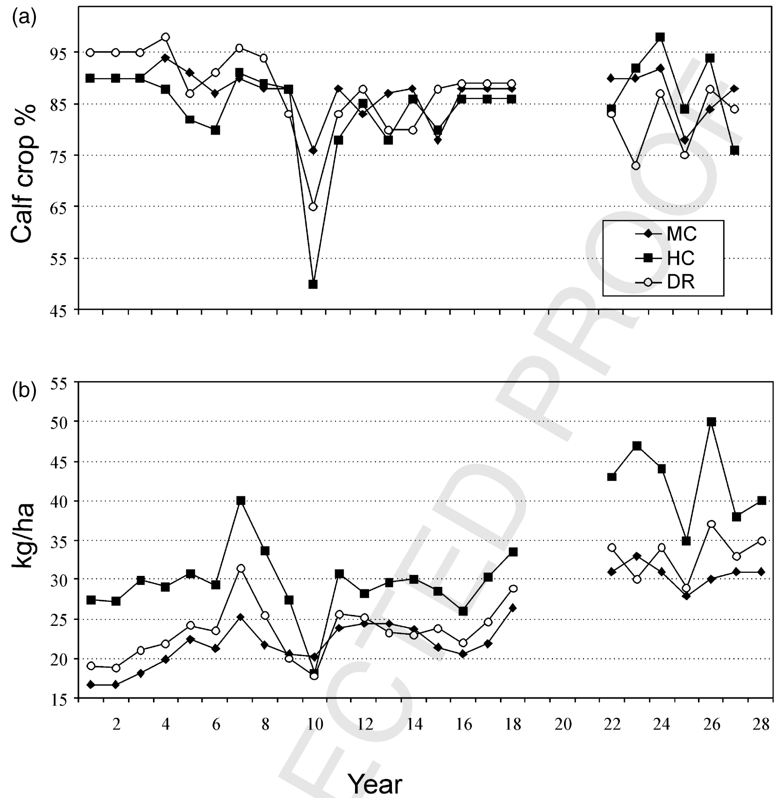

Fig. 2. Field data over the experimental period from 1961 to 1989. (A) number of calves weaned per 100 exposed cows (calf crop%) and (B) mean weaning weight per hectare for the moderate continuous (MC), heavy continuous (HC) and deferred rotation (DR) grazing treatments. Purebred Herefords were used from 1961 to 1978 and Charolais bulls were bred to Hereford×Angus crossbred cows from 1979 to 1989.

the standard errors of the field data only for the moderately stocked treatment. The model overestimated live plus dead herbage in the heavily stocked pasture. Even though simulated standing crop for the most common soil series closely matched field standing crop values at this site (Foy et al., 1999), the model did not simulate treatment differences well when the actual proportions of soil series in each treatment were simulated. Regression values were high for all simulations because the monthly standing crop of herbage through each year was predicted closely, as indicated by Foy et al. (1999).

Standing crop is comprised of three perennial components; C_4 shortgrass, C_4 midgrass and C_3 wintergrass, and an annual component, C_3 annual grass. The standing crop of C_4 shortgrass was simulated well by SPUR2.4 (Fig. 4). For shortgrass the live standing crop values simulated by the model fell within one standard error of the field data means at both moderate and high stocking rates. The shortgrass live plus dead was overestimated with both MC and HC treatments, but the relative

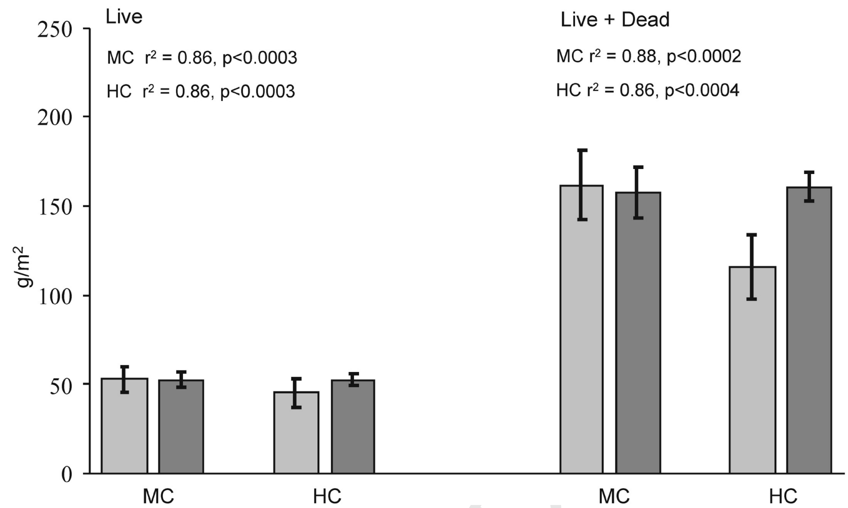

Fig. 3. Standing crop simulated by SPUR2.4 (▬) compared with mean monthly standing crop at the Texas Experimental Ranch (▭) from 1961 to 1989 for moderate continuous (MC) and heavy continuous (HC) grazing treatments.

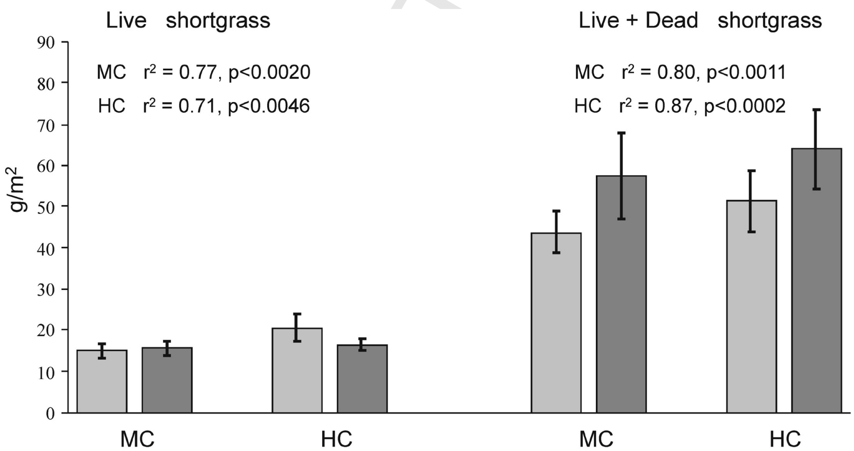

Fig. 4. Standing crop of C_4 shortgrass simulated by SPUR2.4 (▬) compared with mean monthly C_4 shortgrass standing crop at the Texas Experimental Ranch (▭) from 1961 to 1989 for moderate continuous (MC) and heavy continuous (HC) grazing treatments.

difference between them was correctly simulated. Similarly, the live component of C_4 mid-grass was estimated accurately and the live plus dead component of moderately and heavily stocked pastures were within the standard errors of the field data (Fig. 5).

The third major herbage component in this rangeland is C_3 wintergrass. The live wintergrass component simulation was within the standard error of the data for the MC treatment but not for the HC treatment, but the relative difference between MC

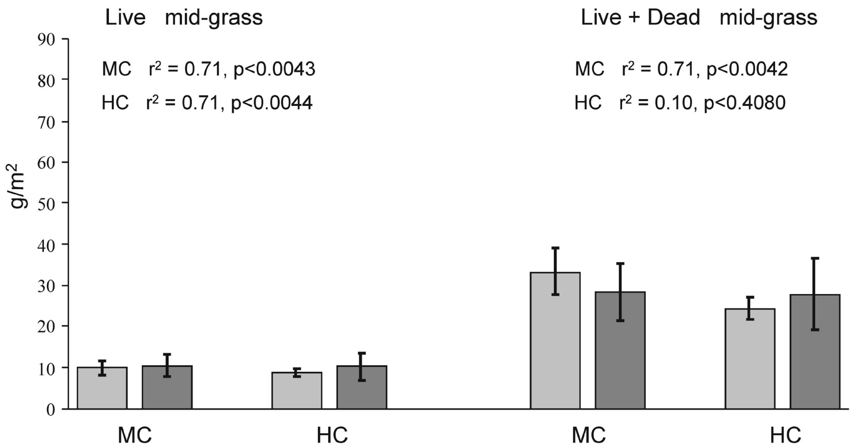

Fig. 5. Standing crop of C_4 mid-grass simulated by SPUR2.4 ( ) compared with mean monthly C_4 mid-grass standing crop at the Texas Experimental Ranch ( ) from 1961 to 1989 for moderate continuous (MC) and heavy continuous (HC) grazing treatments.

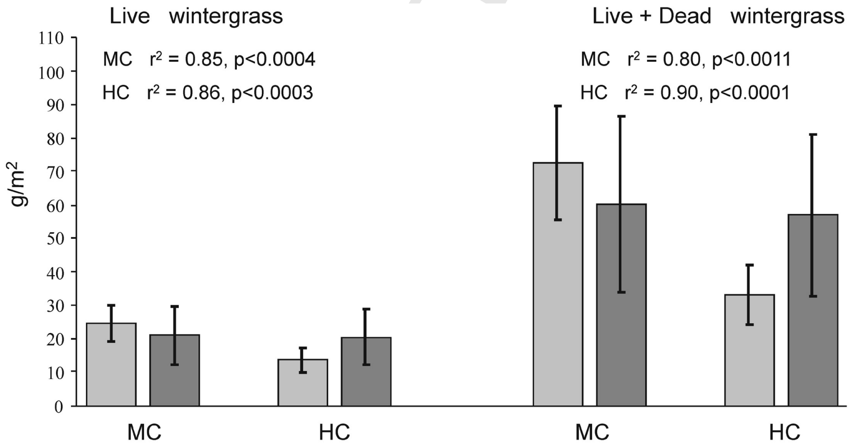

Fig. 6. Standing crop of C_3 wintergrass simulated by SPUR2.4 ( ) compared with mean monthly C_3 wintergrass standing crop at the Texas Experimental Ranch ( ) from 1961 to 1989 for moderate continuous (MC) and heavy continuous (HC) grazing treatments.

and HC was correctly simulated. The live plus dead component was within the standard error of the data for the MC but the live plus dead for HC wintergrass was overestimated (Fig. 6). However, the model correctly predicted higher MC standing crops than HC standing crops for the live plus dead wintergrass components. The high predictions for total wintergrass are the main reason total standing crop of all species was overestimated for the HC treatment.

The model did not predict either live or live plus dead standing crop of C_3 annual grass within the standard errors but did predict values for annual grass that are the

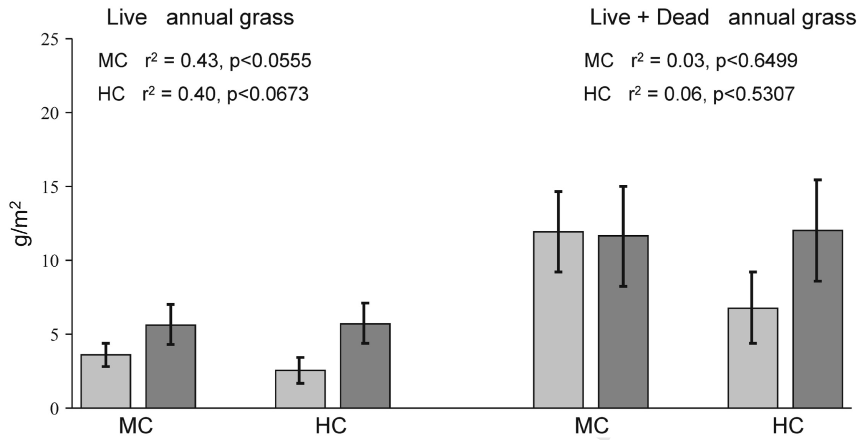

Fig. 7. Standing crop of C_3 annual grass simulated by SPUR2.4 ( ) compared with mean monthly C_3 annual grass standing crop at the Texas Experimental Ranch (( ) from 1961 to 1989 for moderate continuous (MC) and heavy continuous (HC) grazing treatments.

same order of magnitude as the measured standing crop (Fig. 7). Live plus dead for MC was accurate but for HC it was overestimated. Annual grass production is notoriously variable (Kothmann et al., 1978) and was probably the reason that model output was not consistently higher or lower than field data. Annual grass is important since it provides a high protein diet for animals for approximately a month in late winter when herbage quality is generally low. Fortunately, annual grass production was relatively small compared with perennial grass production so this inaccuracy and variability does not materially influence secondary productivity.

The model was originally written using data from shortgrass prairie in the northern Great Plains. Foy et al. (1999) have previously indicated that SPUR predicts shortgrass and mid-grass adequately and that while live wintergrass was reasonably well simulated, live plus dead wintergrass was over-predicted for the HC treatment. The inability to accurately predict total wintergrass biomass is not serious when considering livestock performance. This grass is readily eaten when in the vegetative stage but becomes very unpalatable when mature, and little dead material is consumed by livestock. Wintergrass consumption is mostly confined to live wintergrass, which is accurately predicted.

3.2. Livestock production

Mean annual weaning weights from the three grazing management treatments are presented in Fig. 8. The model accurately predicted the higher weaning weights measured from the Charolais-cross calves compared with the purebred Hereford calves. In addition, the model predictions were within the standard errors of both purebred Herefords and the Charolais-crosses in all treatments except Herefords at the high stocking rate. However, the treatment differences measured in the field were not accurately simulated. The model incorrectly predicted almost identical weaning

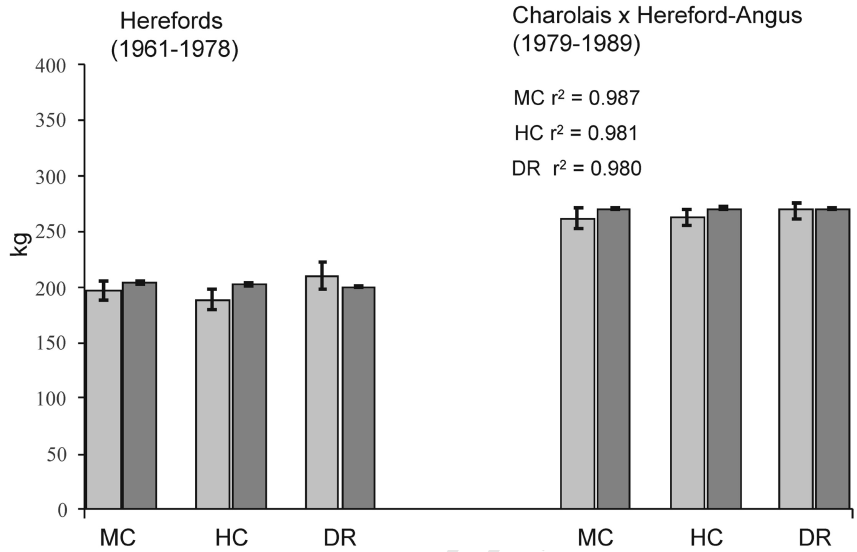

Fig. 8. Annual weaning weight simulated by SPUR2.4 (▭) compared with mean weaning weight at the Texas Experimental Ranch (▭) from 1961 to 1989 for moderate continuous (MC), heavy continuous (HC) and deferred rotation (DR) grazing treatments.

weights for both the Hereford and Charolais-cross calves in all treatments. This error was caused by the inability of the model to accurately predict the herbage availability and quality in the treatment areas that have different proportions of each soil series in the treatments as noted earlier. Foy et al. (1999) have previously indicated that SPUR2.4 accurately simulated ($r^2 > 0.98$) weaning weights for the most common soil series at this site.

The model accurately predicted the mean weaning weights per hectare of all treatments and the differences between treatments for both the Hereford and Charolais-cross calves (Fig. 9). Only the simulation of Charolais-cross calves in the deferred rotation treatment fell outside the standard error of the field data, but the treatment ranking was correct and the regression values were high for this simulation. Clearly the animal production and genetic routines of the model provided very good estimates of the animal data collected in this field experiment with animals having very different genetic backgrounds.

4. Conclusions

SPUR2.4 simulates a number of parameters well enough to be used as a decision aid but improvements have to be made if it is to be generally useful as a decision aid. In particular, the cow-calf production and genetic portions of the model appear to be performing well as illustrated in this paper and previous publications (Carlson and Thurow, 1996; Foy et al., 1999). Weaning weight per hectare of Hereford and

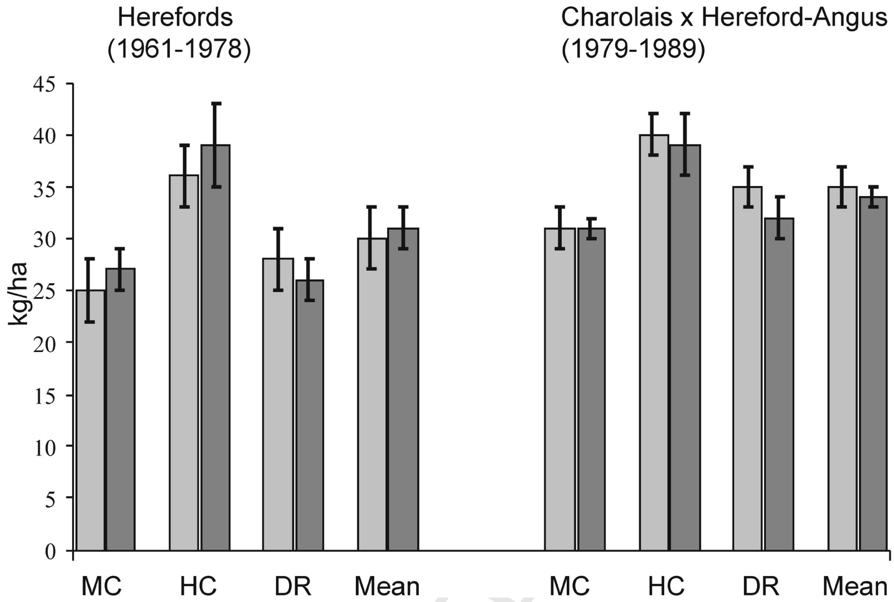

Fig. 9. Mean weaning weight per hectare simulated by SPUR2.4 (▬) compared with mean weaning weight per hectare at the Texas Experimental Ranch (▭) from 1961 to 1989 for moderate continuous (MC), heavy continuous (HC) and deferred rotation (DR) grazing treatments.

Charolais-cross animals were accurately simulated in all three treatments, including correct estimates of treatment rank and differences.

Simulation of primary productivity for C_4 shortgrass was good, adequate for C_4 mid-grass and live C_3 wintergrass, but inadequate for total wintergrass, as illustrated in this paper and by Foy et al. (1999). The productivity of C_3 annual grass predicted by SPUR2.4 was of the same order of magnitude as productivity measured in the field and appears to be adequate in terms of predicting secondary production. To get good predictions of animal production the model must correctly predict the standing crop and proportion of live and dead herbage as well as the quality and the proportional consumption of herbage species which differ in palatability. SPUR2.4 predicts cow and calf weights well on single soils (Foy et al., 1999) so all these parameters are adequately simulated.

However, the model did not correctly simulate primary production from an area of land with more than one soil series. This limitation significantly detracts from its utility. When a single soil was used, simulations of soil moisture and live standing crop of all species groups generally fell within one standard error deviation of field data (Foy et al., 1999). Therefore, the lack of ability to simulate accurately with more than one soil was related to model structure in collating herbage standing crop with different soils, rather than to simulation of the biological herbage growth process and the other factors determining secondary production. This structural flaw must be corrected before the model will adequately simulate secondary productivity for large landscapes that contain different soil series. It will probably require parameterization of individual soils to solve this problem.

One of the major simplifying assumptions made in SPUR was that vegetation and vegetation use over a grazing unit, are uniform. While this may be a reasonable approximation for the relatively small areas used for most research purposes, one of the major areas of concern at the ranch scale is the differential use and different distribution of preferred vegetation patches and areas around water points and waterways. The resulting uneven distribution of animal impact has significant effects on the range vegetation, hydrology and water quality and is influenced significantly as size of the grazing unit increases (Coughenour, 1991; Norton, 1998). Such phenomena compound over time and have a major long-term impact on the environment and primary and secondary production (Fuls and Bosch, 1991; Kellner and Bosch, 1992). A spatial capability, such as a link to a GIS, or incorporation of a pseudo-GIS, is needed to address these issues.

Acknowledgements

We thank Steve Dowhower and Bill Pinchak for providing data from the Texas Experimental Ranch. We thank Mort Kothmann, Charles Long, Bill Pinchak, Don Robinson, Mark Weltz and two anonymous reviewers for very useful comments on an earlier draft.

Appendix

Table A1
Abbreviations used in the text

Abbreviation	Description
AUY	Animal unit year. The potential animal demand of a 450 kg, non-lactating cow or its equivalent, for a full year
C_3	Cool-season plants, employing the pentose phosphate pathway of carbon dioxide assimilation during photosynthesis
C_4	Warm-season plants, employing the dicarboxylic acid pathway of carbon dioxide assimilation during photosynthesis
DR	Deferred rotation grazing system, with four pastures and three cow herds. Each pasture is grazed continuously for a year and then rested for 4 months in a sequence that provides deferment at a different season at each subsequent deferment
GIS	Geographic Information System
HC	Heavily stocked continuous grazing with no deferment.
MC	Moderately stocked continuous grazing with no deferment
TER	Texas Experimental Ranch, Throckmorton, Texas

Table A2
Animal mass and heterosis values used to parameterize the genetics portion of the livestock submodel in the SPUR2.4 simulations

Genetic background	Trait											
	Birth weight			Year weight			Mature weight			Milk production		
	Sire (kg)	Dam (kg)	Heterosis (kg)	Sire (kg)	Dam (kg)	Heterosis (kg)	Sire (kg)	Dam (kg)	Heterosis (kg)	Sire (kg)	Dam (kg)	Heterosis (kg)
Hereford	25	25		235	230		450	395		7.0	8.0	
Hereford× Angus[a]		31			190			415			7.5	
Charolais	31.5			460			650			7.0		
Angus× Hereford			−0.96			+21.0			+11.35			+0.44
Hereford× Angus			+2.29			+10.28			+11.35			+0.44
Charolais× Angus			+4.86			−8.34			+23.81			+0.44
Charolais× Hereford			+4.86			−8.34			+23.81			+0.44

[a] First name in a cross is sire breed.

Table A3
Parameter values that affect the magnitude and timing of plant growth in the SPUR2.4 simulations

Parameter	Unit	Description	Species			
			C_3 Annual grass	C_3 Wintergrass	C_4 Shortgrass	C_4 Mid-grass
P1	mg dm^{-2} h^{-1}	Maximum photosynthetic rate	12	18	32	23
P3	°C	Maximum temperature for plant activity	37	39	42	40
P4	°C	Optimum temperature for plant activity	17	22	25	25
P5	°C	Minimum temperature for plant activity	−3	−1	3	8
P9	in/in	Root to shoot ratio	2	4	7	7
P10	km	Wind tolerance coefficient	−0.00032	−0.00024	−0.00016	−0.00016
P11	cm	Precipitation tolerance coefficient	−0.44	−0.32	−0.20	−0.20
P12	Proportion	Proportion of phytomass susceptible to trampling	0.05	0.05	0.06	0.06
P13	Ha/animal	Stocking rate tolerance of standing dead	−0.009	−0.009	−0.010	−0.010
P14	Ha/animal	Stocking rate tolerance of green shoots	−0.005	−0.005	−0.006	−0.006
P15	Proportion	Proportion of green shoots to die	0.007	0.007	0.007	0.007
P16	m^2 g^{-1}	Leaf conversion factor	0.0120	0.0160	0.0072	0.0130
P24	Proportion	Root respiration proportion	0.0020	0.0025	0.0025	0.0035
P25	Proportion	Root mortality proportion	0.020	0.009	0.010	0.014
CRIT1	area/area	Maximum live leaf area index	0.20	1.25	0.30	0.90
CRIT3	°C	Temperature for translocation	6	14	9	10
CRIT4	bars	Water potential for translocation	−3	0	−28	−17
CRIT5	bars	Water potential for germination	−6	−3	−5	−4
CRIT6	Julian day	Day seed production begins	230	200	210	210
CRIT7	Julian day	Day senescence begins	245	220	215	220
CRIT8	Julian day	Day senescence ends	270	365	280	280
PNS1	Proportion	Decomposition rate—dead roots	0.0013	0.0013	0.0013	0.0013
PNS2	Proportion	Decomposition rate—litter	0.023	0.023	0.023	0.023
PNS3	Proportion	Decomposition rate—soil organic matter	0.00046	0.00046	0.00046	0.00046

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