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A Simulation Approach for Evaluating Field Data from Grazing Trials*

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ABSTRACT

A simulation model was developed to provide a tool for evaluating data from a field trial beyond that typically available from statistical analysis. Field data that estimated diet dry matter digestibility, fecal output, and grazing activity were used as driving variables to calculate and compare the energy and weight flux of cattle on continuous and rotational grazing systems. The results indicated that the cumulative effect of small (statistically non-significant) differences in the driving variables could result in observed differences in animal performance. The results indicated that diet dry matter digestibility may have been underestimated by the data and the difference between grazing treatments in fecal output may have been overestimated by the data. These apparent discrepancies between model performance and the field data were biologically interpretable. Sensitivity analysis indicated that a 1% change in diet dry matter digestibility, fecal output, and grazing activity resulted in a 4·4, 0·5, and 0·1% change in simulated calf weaning weight, respectively.

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INTRODUCTION

Process oriented field studies examining the effects of various grazing treatments on livestock production often fail to adequately account for observed differences in livestock production. This is because livestock production is an integrated measure of the cumulative effects of numerous processes. Simulation models provide an effective tool for examining the effects of various treatments on specific processes as well as their cumulative effect on livestock production. Therefore, a model was developed to augment the understanding of results from an experiment that compared rotational and continuous grazing. The impetus for developing the model was the availability of a rather comprehensive set of data on the processes and performance of cattle on rotational and continuous grazing systems (Heitschmidt, 1986). Statistical analysis of the data indicated that there were no or only small differences in diet quality (Walker *et al.*, 1989) and nutrient intake (McKown, 1987) between the two grazing treatments. Animal behavior and performance did vary between the treatments (Heitschmidt *et al.*, in press; Walker & Heitschmidt, 1989). We were interested in determining if field data, on the various processes that we believed influenced animal performance on rangelands, were sufficiently accurate to stimulate cattle performance and predict grazing treatment effects.

The model uses NRC (1984) guidelines and other empirical relationships to predict the weight of a grazing cow and calf using actual field data for energy intake and energy expended for grazing activity. This model differs from other beef cattle models because it was built to address very specific objectives. As a result this model is much simpler than most previous beef cattle models. The objectives of this model were to: (1) determine if field data from different grazing systems and generally accepted empirical relationships could be used to predict observed differences in animal performance; (2) use model sensitivity to field parameters as a tool to improve the design of future grazing research; and (3) provide a tool for investigating the effects of certain aspects of rotational grazing on cattle performance.

EXPERIMENTAL DESIGN

The field study was conducted at the Texas Experimental Ranch located (99°14′W, 33°20′N) on the eastern edge of the Rolling Plains resource region. The climate is continental, semi-arid, and highly variable. Annual precipitation is bimodally distributed and averages 682 mm. Peak precipitation months are May (96 mm) and September (118 mm). Average maximum daily temperatures range from 11·4°C in January to 35·8°C in

July. Average minimum daily temperatures range from −2·4°C in January to 22·0°C in July. For a complete description of the study area see Heitschmidt *et al.* (1985).

The two grazing treatments studied were rotational grazing (RG) and continuous grazing (CG). The RG treatment was initiated in March 1981 in a 465-ha, cell-designed (paddocks radiating from a common center) grazing facility. Initially the treatment consisted of 14 paddocks that averaged 33 ha in size. In March 1982 a 30-ha paddock was divided twice creating three 10-ha paddocks for a total of 16 paddocks in the RG treatment. Rate of rotation was flexible and varied according to vegetation growth rates and nutrient requirements of the cows. Days of rest between grazing periods ranged from 30 to 65. The treatment was originally stocked at a heavy rate of 3·7 ha/cow/year. Stocking rate was constant until June 1984 when it was reduced to 5·2 ha/cow/year because of drought. Stocking rate on the different size study paddocks was kept constant by varying the length of graze. Cattle in the RG treatment were supplemented during the winter with a 20% crude protein cube (3·3 mcal DE/kg) fed at the rate of 1·4 kg/day for about 90 days beginning after the middle of December. Data were collected on five paddocks including three 10-ha paddocks and two 27-ha paddocks. The CG treatment was a single 248-ha pasture that had been stocked at a moderate rate since 1960 and was stocked at 5·9 ha/cow/year throughout this study. Cattle in the CG treatment were not supplemented except on an emergency basis due to snow cover. Both treatments were grazed by Angus × Hereford crossbred cows (average weight 450 kg) bred to Charolais bulls (average weight 775 kg). The breeding season was from April through June and calves were weaned in October. For a complete description of vegetation and study design, see Heitschmidt *et al.* (1987).

Eight seasonal trials were conducted between October 1982 and August 1984. Trial dates corresponded to periods when cattle in the RG treatment were rotated through the study paddocks in the grazing cell. Both treatments were sampled simultaneously. Diets were collected using esophageally fistulated steers (Walker *et al.*, 1989). Fecal output was estimated from the same steers using ytterbium nitrate as an external marker (McKown, 1987). Grazing behavior was measured on cows using vibracorders and pedometers (Walker & Heitschmidt, 1989). Cattle were weighed in April, June, August, October, and December each year (Heitschmidt *et al.*, in press).

MODEL STRUCTURE

The conceptual model structure is shown in Fig. 1, the symbols follow the style of Forrester (1961), and variables are defined in Table 1. The model

TABLE 1
Symbols and Definitions of Model Components

Symbol	*Unit*	*Definition*
State variables		
ENGCOW	mcal	Gross energy in cow
ENGCALF	mcal	Gross energy in calf
WTCOW	kg	Weight of cow without conceptus
WTCALF	kg	Weight of calf
Auxiliary variables		
COND	none	Cow body condition
EBCOW	mcal	Cow energy balance (*T1* – *T3* – *T2*)
EBCALF	mcal	Calf energy balance (*T3* + *T4* – *T5*)
LWCOW	kg	Cow live weight (*WTCOW* + conceptus)
Driving variables:		
Grazing treatment dependent		
FECES	%	Fecal output as a per cent of body weight
IVDDM	%	In-vitro digestible dry matter
GRAZE	h	Time spent grazing
TRAVEL	km	Distance traveled
Grazing treatment independent		
PREG	mcal	Energy cost of pregnancy
SEASON	%	Increase in maintenance requirements due to seasonal climatic effects
LACT	mcal	Maximum potential GE in milk

includes two component submodels: energy flow (mcal) and weight flow (kg). For the purpose of model simplification a nitrogen component was not included. Based on the supplementation regimen applied and previous data (Kothmann *et al.*, 1970) we believe that nitrogen was not limiting under the conditions of this study. The model simulates a single reproducing mature female (5–9 years old) and simulation begins on 1 October. At this time the cow is dry and in the second trimester of gestation. Calves are born 1 February and weaned 30 September. This time sequence corresponds to the field situation that was modeled. The model is a difference equation model operating at a 1-day time step. It is coded in BASIC and was developed with the aid of TIME-ZERO software (Kirchner, 1987). Predicted differences in energy and weight flux between the two grazing treatments were the result of variations between treatments in four driving variables (i.e. *IVDDM*, *FECES*, *GRAZING*, and *TRAVEL*; Fig. 2). These driving variables were derived from the eight field trials. The continuous functions used in the model to represent these data were developed using multiple regression to fit a polynomial equation to these data with time as the independent variable.

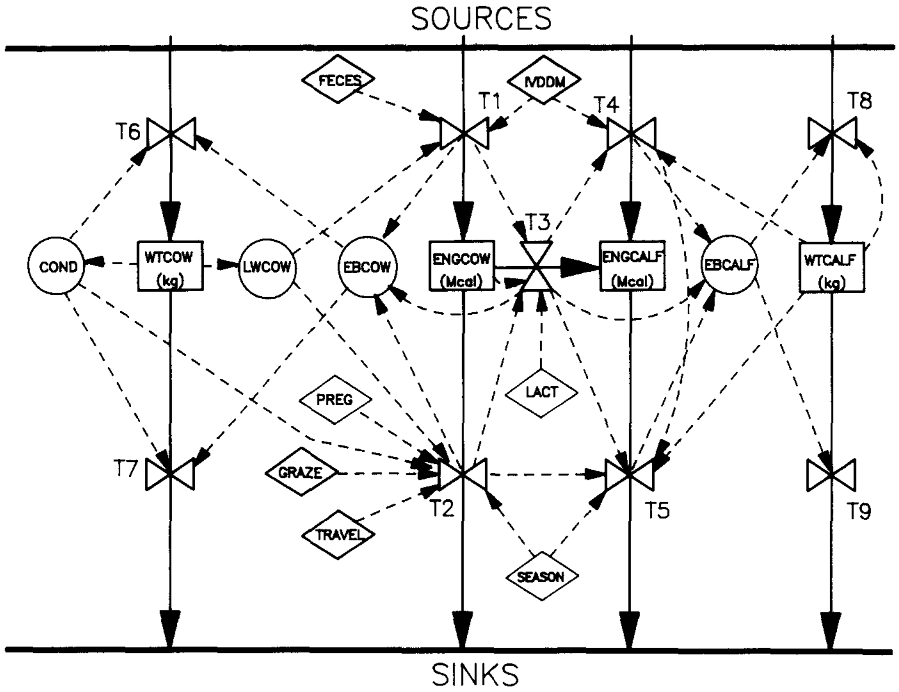

Fig. 1. Conceptual model diagram of cow and calf model. Variables are defined in Table 1.

Energy submodel

The energy submodel calculates the energy intake of a cow and calf from forage, energy transferred from the cow, to the calf via milk, and the energy cost of maintenance. All flows in the energy submodel have units of mcal/day. Energy transfer from the cow, to the calf *in utero* was modeled as a maintenance cost for the purpose of model simplification.

$T1$, the transfer of energy into the cow, is the product of forage intake on a percentage of live weight basis, energy density in the forage, and cow live weight ($LWCOW$):

$$T1 = INTK \cdot LWCOW \cdot NEm \tag{1}$$

Forage intake ($INTK$) is calculated from fecal output ($FECES$) and diet in-vitro digestible dry matter ($IVDDM$) as follows:

$$INTK = FECES \cdot (1 - IVDDM)^{-1} \tag{2}$$

Because intake estimates were based on data from steers, adjustments were made to account for the effects of pregnancy and lactation on intake (NRC, 1987). This assumes that relative differences in intake between steers and cows are caused by differences in production demands. Intake adjustments

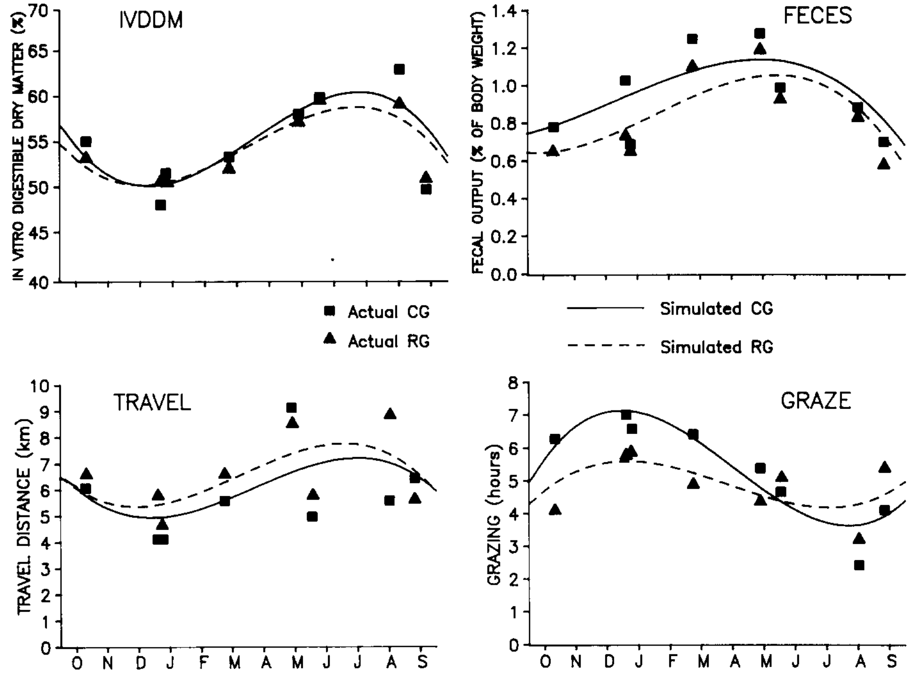

Fig. 2. Actual data and continuous functions used to estimate these data for the four driving variables that differed because of grazing treatment.

were made by varying the level of *FECES* because these variations in intake are apparently caused by a change in rumen volume (Forbes, 1970) and result in a change in fecal output (Field, 1970). Therefore, the actual level of *FECES* was decreased 4 weeks prior to parturition and increased after parturition according to NRC (1987) intake adjustment guidelines. Energy density of the diet is calculated from *IVDDM* using the equation of Rittenhouse *et al.* (1971) to predict digestible energy (*DE*). Digestible energy is converted to metabolizable energy (*ME*) assuming a conversion efficiency (k_m) of 80% and NRC (1984) equations to convert *ME* to net energy for maintenance (*NEm*).

T2, the energy cost of maintenance, is a function of basal metabolic rate (*BMR*), *LWCOW*, energy cost of grazing activities, and energy cost of pregnancy (*PREG*):

$$T2 = BMR \cdot SEASON \cdot COND^{0 \cdot 5} + (GRAZE \cdot LWCOW) + (TRAVEL \cdot LWCOW) + PREG \qquad (3)$$

BMR was calculated as 0·077 mcal/kg$^{0 \cdot 75}$ (NRC, 1984) and adjusted for seasonal environmental effects (*SEASON*) using data from Laurenz *et al.* (1987) and for the effect of body condition using the formula of Sanders &

Cartwright (1979). *COND* was calculated as *WMA*/*WTCOW* where *WMA* is weight at maturity and was set at 455 kg for this model. Energy costs for grazing were calculated from the amount of time spent harvesting forage (*GRAZE*) and the distance traveled (*TRAVEL*). Harvesting time was converted to energy expense assuming 0·000 54 mcal/kg/h (Graham, 1964) as the energy cost of mastication. Distance traveled was converted to energy requirements by assuming 0·000 48 mcal/kg km for horizontal travel and 0·006 21 mcal/kg km for vertical travel (Ribeiro *et al.*, 1977). The energy cost of pregnancy was computed using the NRC (1984) equation for this requirement.

T3, energy transferred from the cow to her calf via milk, was a function of the energy derived from consumed forage that was in excess of maintenance (*T2*) requirements, energy available from body reserves, and the energy required to meet the cow's lactation potential:

$$T3 = MAXIMUM\ (T5 - T8 + BR,\ LACT) \tag{4}$$

Energy available from body reserves (*BR*) was calculated as described by Sanders & Cartwright (1979) assuming 84% efficiency of mobilization of tissue energy. Potential lactation (*LACT*) was calculated using the lactation curve equation of Wood (1977):

$$y_n = an^b \mathrm{e}^{-cn} \tag{5}$$

where y_n is the quantity of milk produced on day n, a is a scalar directly related to total milk production, b is an indication of the animal's capacity to utilize energy for milk production, and c is a decay rate. Values determined by Holloway *et al.* (1982*b*) for Angus cattle on fescue pasture were used for the latter two parameters. The parameter that determines total milk production was estimated during model parameterization. *GE* content of the milk was estimated using the NRC (1984) equation assuming a milk fat content of 5% (Chenette & Frahm, 1981). Milk *GE* was converted to *NEm* assuming efficiency of conversion of 95% for *GE* to *DE*; 82% for *DE* to *ME*; and 70% *ME to NEm.*

T4, the transfer of energy to the calf from the forage source, was not measured during the field trials. Therefore, this transfer was calculated using the response surface equation of Holloway *et al.* (1982*a*), whereby *DE* intake/kg calf weight varies as a function of milk energy intake and *DE* content of forage. The equation is as follows:

$$CFE = 0{\cdot}04 + 3{\cdot}75X_1 - 24{\cdot}32X_1^2 - 0{\cdot}08X_2 + 0{\cdot}03X_2^2 - 1{\cdot}03X_1X_2 \tag{6}$$

where *CFE* is calf forage *DE* intake per kg weight (mcal $DE \cdot \mathrm{kg}^{-1}$), X_1 is milk *DE* intake per kg weight, and X_2 is forage *DE* concentration. This response surface predicts that forage *DE* intake is positively related to forage *DE* concentration and inversely related to milk intake.

T5, calf maintenance costs are affected by *BMR* adjusted for season as described for cows and by foraging activity (i.e. grazing and travel):·

$$T_5 = BMR \cdot SEASON + (BMR \cdot F \cdot (T4/(T4 + T3))) \tag{7}$$

Foraging activity was not measured on calves in the field. The model calculates the energy cost of foraging activity in calves (*F*) from the energy costs of foraging in cows relative to their basal metabolic requirements ($F = [GRAZE + TRAVEL] \cdot BMR^{-1}$), and the proportion of the calves' total energy intake provided by forage. Thus as energy intake from forage increases relative to energy intake from milk, the energy expended for foraging also increases.

Weight submodel

Weight flux of the cow and calf was a function of the balance between *NEm* intake and *NEm* requirement, and the energy density of the body tissue:

$$EBCOW = T1 - T2 - T3 \tag{8}$$

and

$$EBCALF = T3 + T4 - T5 \tag{9}$$

EBCOW and *EBCALF* are the *NEm* balance for cows and calves, respectively. If the *NEm* balance was positive then *NEm* was converted to net energy for gain (*NEg*) (NRC, 1984) based on the difference in the efficiency of use of *ME* for these two processes. If the *NEm* balance was negative, then body tissue was mobilized to meet the deficit with an efficiency of mobilization from stored energy to *NEm* of 84%. The energy content of tissue was set at 7·0 mcal/kg for cows in average condition. Energy content of tissue varied as a function of $7{\cdot}0\ \mathrm{mcal/kg} \cdot (1/COND)^a$. The parameter '*a*' was estimated to be equal to 0·5 during initial model calibration. The actual live weight (*LWCOW*) of a cow was calculated as an auxiliary variable because the energy contained in the conceptus was not modeled directly and *LWCOW* was necessary for input into the energy submodel. *LWCOW* was calculated by adding the weight of the conceptus (Silvey & Haydock, 1978) to *WTCOW*. If *EBCALF* was positive, weight gain of calves was calculated according to the NRC (1984) equation for estimating live weight gain of large frame steers from *NEg*. If *EBCALF* was negative, weight loss of steers was determined in the same manner as it was calculated for cows except that the energy content of the tissue was kept at a constant 7·0 mcal/kg.

Parameter estimation

Because initial simulations did not produce reasonable predictions of cattle weights, several parameters were modified as part of model construction. The variables that were adjusted included *IVDDM*, *FECES*, *LACT*, calf *DE* intake from forage, and energy cost of calf grazing activity. The adjustment was made by estimating the value of the intercept in the function that described each of these variables. The equation for the energy cost of grazing by calves did not have an intercept so this variable was adjusted with a multiplicative factor. All adjustments changed only the level of the variables and did not affect their functional form. Parameters were estimated using the Hooke & Jeeves (1961) method to minimize an objective function. The objective function was the sum of the squared differences between actual and predicted cow and calf weight in the CG treatment plus a weighting factor for each of the parameters that were estimated. The weighting factor was an exponential function that increased the value of the objective function if the estimated value of a parameter deviated from the initial value. Thus the parameter estimation procedure was a constrained optimization technique that assured the estimated parameters would remain within a plausible range. An exponential function was used for the weighting factor because we believed that the initial values of variables for which adjustments were estimated were reasonably accurate and large adjustments would not be reasonable. The nonlinear form of the exponential function resulted in proportionately greater weighting factors as the difference between the initial and estimated parameter values increased. To make comparisons between the two treatments when the model was parameterized for the CG treatment, the difference between the initial and estimated parameter value estimated for the CG parameters was added to the same parameter in the RG treatment.

RESULTS

Parameter estimation

The results of the parameter estimation procedure used to insure that the model fit the field data for the CG treatment are of interest (Table 2). Compared to the field data the simulated values of *IVDDM* and *FECES* were increased an average of 8% and 2%, respectively. This indicates that energy intake estimated from the field data was less than required to meet simulated energy demand. The indication from our model was that the *in vitro* data underestimated *in vivo* digestion by a factor similar to results from

TABLE 2
Initial and Estimated Values of Parameters that were Estimated During Model Construction to Minimize the Difference Between Actual Cow and Calf Weights in the Continuous Grazing Treatment and Weights Predicted by the Model

Parameter	*Parameter value*			
	Units	*Initial*	*Estimated*	*Average % change*
IVDDM intercept	%	57·5	62·5	8·0
FECES intercept	% of body weight	0·75	0·76	1·9
LACT size parameter	kg/day	1·05	1·40	33·0
Calf *DE* intake intercept	mcal DE/(day · kg wt)	0·042	0·066	80·0
Calf activity adjustment	unitless	1·0	0·53	−47·0

previous studies that have compared these procedures (Kartchner & Campbell, 1979; Brooks & Urness, 1984; Holechek *et al.*, 1986). The use of external markers to estimate fecal output has been shown to both over- and underestimate actual fecal output (Galyean *et al.*, 1987). The small estimated adjustment to the *FECES* intercept in this model may indicate that the use of daily dosed ytterbium nitrate in the field portion of this study provided an accurate estimate of fecal output and agrees with the reliability of this technique reported by Prigge *et al.* (1981).

The scaling factor (i.e. a in eqn (5)) for the lactation curve estimated during model parameterization resulted in an estimate of average daily milk production equal to 5·8 kg/day during the 245 day lactation. This estimate of milk production was 33% greater than that estimated for Angus cows (Holloway *et al.*, 1982*b*) and 15% greater than Angus × Hereford cows (Jenkins & Ferrell, 1984).

The intercept of the equation used to estimate calf energy intake from forage (Holloway *et al.*, 1982*a*) had the greatest adjustment as a result of the parameter estimation procedure. The adjusted equation resulted in an average increase of 80% in simulated forage DE intake per kg calf weight relative to the initial estimates. Because forage energy intake is negatively related to milk energy intake the large adjustment was probably due to the greater simulated milk production in this model relative to that estimated by Holloway *et al.* (1982*a*).

The logic used to predict the energy cost of grazing activity in the calves overestimated this variable by 47% based on the parameter estimation procedure. However, this estimated adjustment was apparently caused by a decline in forage digestibility late in the season which the optimization procedure tried to adjust for by decreasing the energy requirements of the calves. We believe that the shape of the *IVDDM* function may have fit the actual late summer forage digestibility poorly and the calculations for energy expenditures for grazing were more suitable than indicated by estimated adjustment required to minimize the objective function.

Model performance

After adjusting the variables with the optimization procedure, the model predicted weights of cattle in the CG treatment at an acceptable level of accuracy (Fig. 3). Although this accuracy was expected and does not represent model validation, we believe that it indicates that the model structure was adequate for the objectives of this study. Discrepancies between predicted and actual weights are probably the result of the shape of the function that estimated *IVDDM* and to a lesser degree the shape of the *FECES* function. We would hypothesize that estimated *IVDDM* in the late summer and fall were underestimated relative to their estimates in the spring. The ability of the model to predict the effect of grazing treatments on animal weights is a better test of model performance, because the optimization procedures tended to assure good prediction for the continuous treatment. For this test of model performance, the difference between the initial and estimated values of the parameters in the CG treatment (Table 2) was added to these parameters in the rotational grazing treatment. The initial simulation resulted in a difference in calf weaning weight of 64 kg compared to an actual difference of 13 kg (Fig. 4). We hypothesized that of the driving variables that differed because of grazing

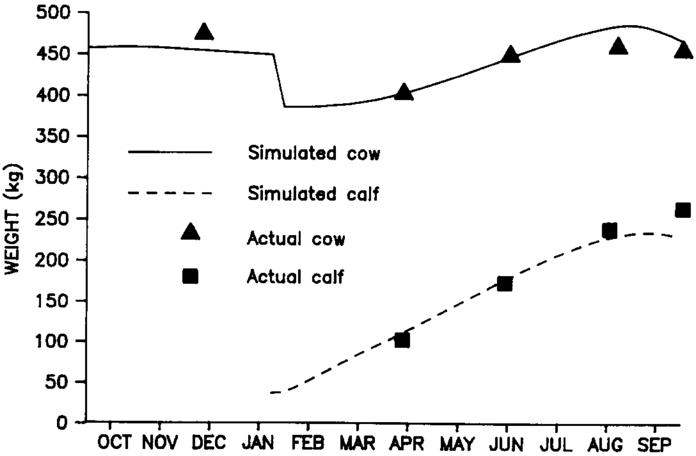

Fig. 3. Actual and predicted cow and calf weights for the continuously grazed treatment.

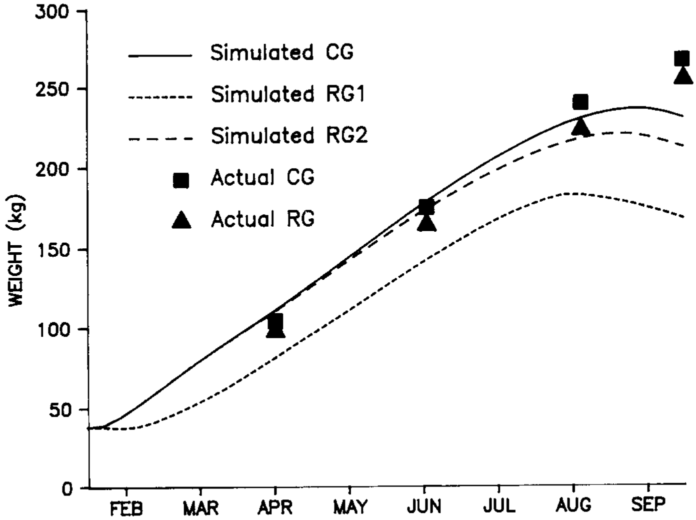

Fig. 4. Actual and predicted calf weights for continuous and rotational grazing treatments. RG1 = simulation using the driving variable equations derived from the RG treatment; RG2 = the same as RG1 except the *FECES* driving variable equation from the CG rather than the RG treatment equation was used.

treatments, *FECES* was most likely to be biased. This was hypothesized because *FECES* was consistently lower in the RG compared to the CG treatment. We would expect fecal output to be equal between the two treatments unless forage availability was limiting, which in our opinion was generally not the case. Furthermore, the steers used to estimate *FECES* in the RG treatment were sampled at least twice as intensively as the ones in the CG treatment due to the rapid rotation through many paddocks. This greater disruption to normal activity may have affected the intake of these animals. Based on this logic, we used the same estimate for *FECES* in the RG as the CG treatment and the result was a predicted difference in weaning weight between the two treatments of 19 kg (Fig. 4). This indicates that estimated fecal output on the RG treatment may have been underestimated relative to the CG treatment, but these model results are not conclusive and could have resulted from small biases in other driving variables.

Model sensitivity

The model was exercised to determine the sensitivity of predicted weight to the field variables that drove grazing treatment effects. This was done using a complete factorial sampling design with three levels for each factor (i.e. nominal and ± 10%) for the variables *IVDDM*, *FECES*, and *ACTIVITY* (i.e.

TABLE 3

Sensitivity of Average Cow Weight and Calf Weaning Weight to Variations in *IVDDM*, *FECES*, and Grazing *ACTIVITY*. Sensitivity is Expressed as the Source Sums of Squares as a Per cent of the Total Sums of Squares

Source	*DF*	*Per cent of variation*	
		Average cow weight	*Calf weaning weight*
IVDDM	2	94·00	98·43
FECES	2	5·21	0·86
ACTIVITY	2	0·44	0·15
I × F	4	0·28	0·46
I × A	4	0·02	0·05
F × A	4	0·01	0·01
I × F × A	8	0·00	0·04

the combined energy cost of *GRAZE* and *TRAVEL*). The response variables measured for this sensitivity analysis were calf weaning weight and average cow weight. Analysis of variance was used to partition the variation in the output variables caused by changes in the driving variables (Table 3). The results indicated that *IVDDM* was the major variable affecting predicted animal performance and accounted for 94 and 98% of the variation in cow and calf weights, respectively. *FECES* was the second most important source of variation accounting for 5 and 1% of the variation in cow and calf weights, respectively. *ACTIVITY* plus all 2- and 3-way interactions accounted for less than 1% of the variation in predicted weights. A 1% change in *IVDDM*, *FECES*, and *ACTIVITY* resulted in approximately a 4·4, 0·5, and 0·1% change in predicted weights, respectively. The high sensitivity to variation in *IVDDM* was not surprising because this variable determines energy concentration of the diet and is used in calculating dry matter intake.

CONCLUSIONS

The model provided a useful tool for understanding the relationship between biological process data derived from the field and actual animal performance data. The model indicated that the differences between the mean values for driving variables derived from the field data were of sufficient magnitude to result in differences in animal performance as great as or greater than the actual observed differences in animal performance. Statistical analysis of variables measured in the field had few significant differences between grazing treatments. The model indicated that the mean values of the field data for diet *IVDDM* and the mean difference between grazing treatments for fecal output may have been biased. Diet *IVDDM* appeared to have been underestimated in both treatments while fecal output appeared to have been underestimated in the RG relative to the CG treatment. These biases were consistent with our understanding of the biology of the processes studied, but were not readily apparent from the statistical analyses of the field data. The model also showed that diet digestibility was the major variable influencing predicted animal performance. This indicates that when planning the sampling design for grazing research on the processes that affect animal performance, priority should be placed on accurately estimating diet digestibility. In the prevalent situation of limited resources, these results mean that the accuracy of estimates of fecal output and animal behavior may have to be sacrificed to allocate adequate resources for the estimation of diet quality. We believe that the model has potential for investigating the effect of management on rotational grazing systems such as variations in the length of grazing/rest period.

REFERENCES

Brooks, J., III & Urness, P. J. (1984). Comparison of in vivo and in vitro digestibility of forages by elk. *Journal of Animal Science*, **58**, 963.

Chenette, C. G. & Frahm, R. R. (1981). Yield and composition of milk from various two-breed cross cows. *Journal of Animal Science*, **52**, 483.

Field, A. C. (1970). Studies on magnesium in ruminant nutrition 10. Effect of lactation on the excretion of magnesium and faecal dry matter grazing monozygotic twin cows. *British Journal of Nutrition*, **24**, 71.

Forbes, J. M. (1970). The voluntary food intake of pregnant and lactating ruminants: A review. *The British Veterinary Journal*, **126**, 1.

Forrester, J. W. (1961). *Industrial Dynamics*. Massachusetts Institute of Technology Press, Cambridge, Mass.

Galyean, M. L., Krysl, L. J. & Estell, R. W. (1987). Marker-based approaches for estimation of fecal output and digestibility in ruminants. In *Symposium Proceedings: Feed Intake by Beef Cattle*. ed. F. N. Owens, Oklahoma Agricultural Experiment Station MP, 121.

Graham, N. McC. (1964). Energy costs of feeding activities and energy expenditure of grazing sheep. *Australian Journal of Agricultural Research*, **15**, 969.

Heitschmidt, R. K. (1986). Vegetation and cow–calf response to rotational grazing at the Texas Experimental Ranch. In *Rangelands: A Resource Under Seige, Proceedings 2nd International Rangeland Congress*. ed. P. J. Joss, P. W. Lynch & O. B. Williams, Australian Academy of Science, Canberra, pp. 207–11.

Heitschmidt, R. K., Conner, J. R., Canon, S. K., Pinchak, W. E., Walker, J. W. & Dowhower, S. L. (in press). Cow/calf production and economic returns from yearlong continuous, deferred rotation and rotational grazing treatments. *Journal of Production Agriculture.*

Heitschmidt, R. K., Dowhower, S. L., Gordon, R. A. & Price, D. L. (1985). Response of vegetation to livestock grazing at the Texas Experimental Ranch. *Texas Agricultural Experiment Station Bulletin* 1515.

Heitschmidt, R. K., Dowhower, S. L. & Walker, J. W. (1987). Some effects of a rotational grazing treatment on quantity and quality of available forage and amount of ground litter. *Journal of Range Management*, **40**, 318.

Holechek, J. L., Wofford, H., Arthun, D., Galyean, M. L. & Wallace, J. D. (1986). Evaluation of total fecal collection for measuring cattle forage intake. *Journal of Range Management*, **39**, 2.

Holloway, J. W., Butts, W. T., Jr. & Worley, T. L. (1982*a*). Utilization of forage and milk energy by Angus calves grazing Fescue or Fescue–Legume pastures. *Journal of Animal Science*, **55**, 1214.

Holloway, J. W., Worley, T. L. & Butts, W. T., Jr. (1982*b*). Lactation curves of Angus cows grazing Fescue–Legume or Fescue pastures. *The University of Tennessee Agricultural Experiment Station Bulletin* 616.

Hooke, R. & Jeeves, T. A. (1961). Direct search solution of numerical and statistical problems. *Journal of the Association for Computing Machinery*, **8**, 212.

Jenkins, T. G. & Ferrell, C. L. (1984). A note on lactation curves of crossbred cows. *Animal Production*, **39**, 479.

Kartchner, R. J. & Campbell, C. M. (1979). Intake and digestibility of range forages consumed by livestock. *Montana Agricultural Experiment Station Bulletin 718.*

Kirchner, T. B. (1987). *TIME–ZERO The Integrated Modeling Environment: Reference manual.* Quarternary Software, Fort Collins, CO, 202 pp.

Kothmann, M. M., Mathis, G. W., Marion, P. T. & Waldrip, W. J. (1970). Livestock production and economic returns from grazing treatments on the Texas Experimental Ranch. *Texas Agricultural Experiment Station Bulletin* 1100.

Laurenz, J. C., Byers, F. M., Schelling, G. T. & Greene, L. W. (1987). Seasonal variation in the maintenance requirements of Simmental and Angus cows. *Texas Agricultural Experiment Station McGregor Field Report Technical Report* 87-1.

McKown, C. D. (1987). Nutrient Intake of Steers in a Continuous and a Rotational Grazing System. MS Thesis, Texas A & M University, College Station, Texas.

National Research Council (NRC) (1984). *Nutrient Requirements of Beef Cattle.* (Sixth revised edition) National Academy of Sciences, Washington, DC.

National Research Council (NRC) (1987). Predicting feed intake of food-producing animals cattle. National Academy of Sciences, Washington, DC.

Prigge, E. C., Varga, G. A., Vicini, J. L. & Reid, R. L. (1981). Comparison of ytterbium chloride and chromium sesquioxide as fecal indicators. *Journal of Animal Science*, **53**, 1629.

Ribeiro, J. M. de C. R., Brockway, J. M. & Webster, A. J. F. (1977). A note on the energy cost of walking in cattle. *Animal Production*, **25**, 107.

Rittenhouse, L. R., Streeter, C. L. & Clanton, D. C. (1971). Estimating digestible energy from digestible dry and organic matter in diets of grazing cattle. *Journal of Range Management*, **24**, 73.

Sanders, J. O. & Cartwright, T. C. (1979). A general cattle production systems model: Part 2. Procedures used for simulating animal performance. *Agricultural Systems*, **3**, 289.

Walker, J. W. & Heitschmidt, R. K. (1989). Some effects of a rotational grazing treatment on cattle grazing behavior. *Journal of Range Management*, **42**(4).

Walker, J. W., Heitschmidt, R. K., de Moraes, E. A., Kothmann, M. M. & Dowhower, S. L. (1989). Quality and botanical composition of cattle diets under rotational and continuous grazing treatments. *Journal of Range Management*. **42**, 239.

Wood, P. D. P. (1977). The biometry of lactation. *Journal of Agricultural Science*, Cambridge, **88**, 333.