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Modeling Animal and Forage Response

to Fertilization of Annual Rangelands

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ABSTRACT: The response functions for forage, animal gain, and stocking rate were estimated from data obtained in a three-year fertilization experiment on California annual range. Degree-days; the interactions between degree-days and nitrogen, between degree-days and phosphorus-sulphur, and between nitrogen and phosphorus-sulfur; and the lagged forage variable were significant in explaining the variations in forage growth, animal gain, and stocking rate. The impact of PS was more important in interaction with DD or N than by itself. The correct impact of moisture was not found due to misspecification of the variable in the model. The models for the first year and the three years combined were well behaved; however, the models for the last two years combined neither explained adequately nor behaved well.

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The response of annual rangeland forages to fertilizer has a long history of analysis. Early fertilizer work on annual rangelands in California were field scale studies which showed fertilization would increase forage production, meat production, and profits (Martin and Berry, 1957 and 1970; Martin, Berry and Williams, 1958). Greenhouse studies using range soils (e.g., Jones, 1967) provided response information, but without the repeated effects of grazing animals, results of greenhouse studies do not reflect accurately the natural process which occurs on rangeland. Another type of range improvement studies were small plot trials which were clipped but not grazed (e.g., Raguse, et al., 1980; Hull, et al., 1972). More recent studies have shown the need for re-application of fertilizer at intervals of from 2 to 5 years (Demment, et al, 1987; Vaughn and Murphy, 1982; Wolters and Eberlein, 1986). Caldwell, et al, (1985) concluded that weather variation can be the principal determinant of forage yield. County extension agents have continued to conduct demonstration research projects to provide timely and localized information concerning the response to fertilizers.[1]

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[1]For example, Bell, M. "Range Fertilization Does More than Boost Growth," Range Roundup, Cooperative Extension, University of California, Orland, California, 1981.

Due to the scale and resource requirements of rangeland experiments, there have been very few replicated, multi-year, field-scale range fertilization experiments. Raguse, et al, (1988) conducted a three-year, field scale, replicated experiment at the University of California Sierra Foothill Range Field Station near Marysville, California. The objectives of this current study are to estimate the forage, animal gain, and stocking rate response functions from data reported by Raguse, et al., (1988) and to analyze the economic implications and uses of the responses.

EXPERIMENTAL METHODS AND MATERIALS

The experiments were conducted at the University of California's Sierra Foothill Range Field Station, Browns Valley, Yuba County, in the lower foothill oak woodland zone of the northern Sierra Nevada mountains. An average 750 to 900 mm rainfall is received between mid-October and late April in a typical Mediterranean climate; snowfall is very rare and transient. Herbaceous vegetation, which is almost completely annual, is a variable mixture of grasses, legumes and other forbs. Standard weather observations were collected at the station. Figure 1 presents rainfall distributions for the three years of the experiment. Soil samples were taken from all fields prior to fertilization. Results, previously reported by Raguse, et al., 1984, showed that N, P and S were required for optimal growth of the grass-legume mixture on these soils. Nitrogen was applied as urea; P and S, as a mixture of 0-20-0 and 0-25-0-10S. The N- and PS-carrying materials were separately applied by helicopter on October 5 and 6, 1982. Two replications (13.2-ha fields) of seven fertilizer treatments were applied as follows:

1. Control (each replication was a mean of two fields)
2. 45 kg ha^{-1} N
3. 90 kg ha^{-1} N
4. 45 kg ha^{-1} N, 34 kg ha^{-1} P, 37 kg ha^{-1} S
5. 90 kg ha^{-1} N, 34 kg ha^{-1} P, 37 kg ha^{-1} S
6. - - - 34 kg ha^{-1} P, 37 kg ha^{-1} S
7. - - - 67 kg ha^{-1} P, 74 kg ha^{-1} S

Each year medium-frame, mostly No. 2 muscle thickness yearling beef feeder steers of mixed English breeding were purchased. Yearling heifers, predominantly Hereford and of the same quality, were taken from the station herd. Standard veterinary practices were used to maintain animal health. Initial animal weights were approximately 215 kg. Periodic weights were taken on all animals every 21 to 28 days during the grazing season. Prior to all weighings, animals were held overnight without feed and water. Forage levels were measured immediately prior to each animal weigh date.

Beginning mid- to late-November, each field (replication) was uniformly stocked with animals (initial weight, approximately 215 kg) at 3.3 to 1.65 ha per animal. Stocking rates were adjusted upwards twice during the season with two objectives: first, to equalize grazing pressure (unit weight of animal per unit weight of forage available for grazing) across treatment and, second, to maintain forage allowance values (average kilograms of forage per hectare divided by the average kilograms of animal per hectare) at 10 or less. No animals were removed before the end of the grazing season. Grazing was terminated in the spring when forage quality declined to a point where approximately zero gain could be estimated from previous weighings.

Raguse, et al., (1988) found annual forage production (FP) in the first year for the PS-only treatments exceeded the NPS treatments which, in turn, exceeded both the N-only and control treatments. "In the second year only the PS treatment exceeded the control; in the third year there were no differences. When treatment means were combined, the first year FP exceeded both the second and third years, which were not different from each other. Combining year means showed FP from NPS and PS treatments to be greater than N-only and the control, with neither pair different from each other" (Raguse, et al., 1988, p. 594). Differences in average daily gain for the livestock were few and formed no consistent pattern with respect to fertilizer treatments. Differences in seasonal liveweight gain between treatments were larger in the first year than in the second and third years due to the high rainfall in the first year. The three-year totals for livestock gain showed the two NPS treatments and the higher PS treatment to be higher than all the other treatments and the control; there were no differences within these two groups.

RESPONSE MODEL SPECIFICATION

The data from this experiment allow the estimation of forage, animal gain, and stocking rate response functions to fertilizer from both seasonal data and data for the entire forage season. The conceptual models are developed from knowledge of the biological processes involved and past studies. Stauber and Burt (1973) estimated the response of hay to nitrogen and precipitation. Reid and Thomas (1973) used a water balance model to evaluate forage production and stocking rates in Australia and defined livestock production as a function of weather rather than as a function of forage. Wight, Hanson, and Whitmer (1984) predicted forage production in Montana by using weather records and a forage production model which used the ratio of actual transpiration to potential transpiration as a yield index.

Forage response. Actual forage production under grazing is difficult to measure. Also, grazing both increases and decreases forage production. Grazing can increase forage growth because defoliation delays maturity, thus stimulating re-growth and maintaining quality. Trampling losses, however, reduce the amount of forage consumed. Here, the forage variable for each period within each grazing season was defined as the amount of forage available at the end of each period plus the estimate of forage consumed by the cattle during that period minus the amount of forage available at the end of the previous period:

$$F_{jt} = A_{jt} + I_{jt} - A_{jt-1} \qquad [1]$$

where F_{jt} was the forage produced in pounds/acre on the j^{th} plot in period t, A_{jt} was the forage available in pounds/acre on the j^{th} plot at the end of period t, and I_{jt} was the total estimated intake in pounds on the j^{th} plot during period t. The estimate of forage consumed daily was based on two percent of the animal weight from the beginning of the grazing season to February 15, 2.5 percent from February 15 to March 31, and by three percent after March 31.

The first variables which are incorporated in the conceptual forage response model are the values for the N, P, and S treatment levels. These nutrients are nitrogen, phosphorus, and sulfur. Because P and S were applied in constant proportions to each other, they were included as one treatment. Other variables which affect forage growth include sunlight, moisture, soil type and characteristics, and temperature. While Pendleton, et al., (1983), estimated significant forage responses to these and other variables, this experiment did not provide data sufficient to replicate their model. Consequently, the simplified model describes forage as a function of temperature, moisture, and applied N and PS levels. To quantify temperature, degree days (DD) were calculated using the methods described in George, Olson, and Menke (1988).

The use of rainfall as the moisture variable was not desirable because most of the rainfall in this climate occurs during the colder parts of the growing season (George, Olson and Menke, 1988) and a significant proportion of the growth occurs during the warmer spring period and frequently until rainfall has stopped and soil moisture has been exhausted. Insufficient data were available to enable construction of a water balance model. Instead, a variable was specified which indicated when moisture was assumed to be limiting to forage growth. Since the experiment began after rains started in the fall, the concern for lack of moisture was in the spring. George, Olson, and Menke (1988) assumed that soil moisture becomes insufficient and the summer dry season begins two rainless weeks after the last week which had one inch or more of rain in the spring. This assumption was used to build a lack-of-moisture variable for the forage model; its value was the number of days between weigh dates that occurred after the beginning of the summer dry season. Thus, for the earlier periods in the winter and the early spring, this variable was zero. Later in the spring, this variable began to have positive values as the number of "dry days" increased. Since the variable has positive values which indicate an assumed lack of moisture, the estimated coefficient on this variable was expected to have a negative sign.

Because the forage produced in each period was also dependent upon the growing conditions earlier in the grazing season, the forage variable was lagged by one period.

Since grazing pressures were held relatively constant across treatments by adjusting stocking rates as forage growth differed, a grazing variable was not included in the estimated model.

Based on this discussion, the conceptual forage model is:

$$F_t = f(DD_t, DRY_t, N, PS, F_{t-1}) \quad [2]$$

where

F_t = forage production in the t^{th} period,
DD_t = degree-day units in the t^{th} period,

DRY_t = number of days in the t^{th} period after the summer dry season has begun,

N = N treatment level, and

PS = P treatment level (which was proportional to the S treatment level).

To clarify presentation, the subscripts used to denote treatments and year are not included.

Animal gain response. Even though weight gain is dependent upon the amount of feedstuffs consumed, the animal gain response to fertilizer applications was estimated by the same independent variables as in the forage response model. Specifying animal weight gain as a function of forage production was not statistically proper since forage production was partially estimated from animal weight gain. Thus, the animal gain response model specifies animal weight gain in each period as a direct function of the weather and treatment variables with the lagged forage growth variable included to capture the effects of past impacts:

$$G_t = g(DD_t, DRY_t, N, PS, F_{t-1}) \quad [3]$$

where

G_t = animal weight gain in the t^{th} period for the entire field and all other variables are as previously defined.

Stocking Rate Response. Another way to measure the response to fertilizer was the number of animals that can be grazed per hectare, i.e., the stocking rate. The stocking rate response model was the same as the animal gain response model [3] except that the stocking rate, S, was the dependent variable:

$$S_t = h(DD_t, DRY_t, N, PS, F_{t-1}) \quad [4]$$

where

S_t = number of animals in each 13.2 ha. field in the t^{th} period and all other variables are as previously defined.

The three conceptional models developed above are used in the estimation of response to fertilizer and weather from both seasonal data and annual data.

RESULTS

Raguse, et al (1988), found that the significance of the response to nutrients differed by year. Consequently, the three conceptual models of forage growth [2], animal gain [3], and stocking rate [4] were estimated using 1983 data only; the combined data for 1983 and 1984; and the combined data for 1983, 1984, and 1985. Estimates are made for both the seasonal data and for annual data. Variables by subgroup are:

Weather variables:

DD = degree-day units per period
DD2 = DD squared
LNDD = natural log of DD
DRY = number of days in each period after the summer dry season has begun
DRY2 = DRY squared

Nutrient variables:

N = N treatment level
N2 = N squared
LNN = natural log of N
N84 = N (or LNN) in 1984, 1983 & 1985 = 0
N85 = N (or LNN) in 1985, 1983 & 1984 = 0
PS = P treatment level (which was proportional to the S treatment level)
PS2 = PS squared
LNPS = natural log of PS
PS84 = PS (or LNPS) in 1984, 1983 & 1985 = 0
PS85 = PS (or LNPS) in 1985, 1983 & 1984 = 0

Weather and nutrient interaction variables:

DDN = DD * N
DDPS = DD * PS
DRYN = DRY * N
DRYPS = DRY * PS
NPS = N * PS

Lagged response variable:

LAGFOR = forage lagged one period

ESTIMATES FROM SEASONAL DATA

Measurements were taken of the forage level, animal weights, and stocking rates every two or three weeks in the winter and spring in the experiment. These seasonal data were used to estimate the response of forage growth, animal gain, and stocking rate. The data were for each period between measurement dates and were not accumulated, thus some problems of autocorrelation were avoided. The functional form of choice was quadratic[2] except for the gain model which had the Cobb-Douglas functional form estimated also.

Forage response. In the complete quadratic forage response model for 1983 data only, these variables were significant (P<0.05): DD, DD2, DRY, DRY2, DDN, DDPS, DRYN, NPS, and LAGFOR (Model 1-1, Table 1). All coefficients had the expected signs except DRY and DRY2 which had signs different from expectations. N, N2, PS, and PS2 were not significant (P>0.05) while the interactions between the weather variables and the nutrient variables (DDN, DDPS, and DRYN) were significant. DRYPS was significant (P<0.10). The significance of the interaction variables and not the nutrient variables confirmed the expectation that the response to fertilizer depends upon the weather. LAGFOR, which accounts for previous growth factors not accounted for explicitly, was significant (P<0.01).

The moisture variable, DRY, was formulated to capture the negative impact of decreasing soil moisture in the late spring and early summer period. However, in Model 1-1, DRY had a positive linear effect and a negative quadratic effect -- opposite from what was expected. (The interaction terms, DRYN and DRYPS, had negative signs as expected.) Estimating the model without DRY, DRY2, DRYN, and DRYPS resulted in a lower adjusted R^2 (Model 1-2). A partial F-test on Model 1-1 rejected (P<0.01) the hypothesis that the coefficients of these four variables were equal to zero. However, the incorrect signs on DRY and DRY2 indicated that the moisture variable was incorrectly specified, so the choice between models 1-1 and 1-2 was not obvious.

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[2]Other analysis showed the quadratic form to be superior to either the linear or square root forms. This work is summarized in the appendix.

Upon reconsideration of the experiment, the data from the last grazing period was removed and the model reestimated. During this last period, the rate of forage production, and thus, the animals' average daily gain, decreased (Raguse, et al, 1988). Under these circumstances, an operating ranch would have removed the animals before or during this last period. Thus, retaining the last period may cause the data to not reflect how range would be managed as a ranch. Also, since the moisture variable, DRY, apparently was not specified correctly causing incorrect parameter signs (Model 1-1), removing the data from the last period may remove the biological need for the moisture variable.

The complete quadratic forage response model without the last period (Model 1-3) has results similar to Model 1-1. (DRY2 was excluded to avoid matrix rank problems.) The partial F-test for Model 1-3 did not reject the null hypothesis that the coefficients for the moisture variables were equal to zero except at a low level of significance ($P>0.25$). By deleting the moisture variables, the adjusted R^2 decreased slightly and coefficient signs are as expected (Model 1-4).

To test the response to weather and nutrients in each period without the lagged forage variable, LAGFOR was deleted from the model for 1983 (Model 1-5). This deletion decreased the adjusted R^2 without improving the other coefficient estimates. Thus, Model 1-5 was not accepted. Apparently, the lagged forage variable incorporated other information from past periods which explained part of the growth in the current period.

For 1983 data only, Model 1-4 was accepted as the best model of the forage response to fertilizer. All coefficients had signs as expected. DD, DD2, N2, DDN, DDPS, NPS, and LAGFOR were significant ($P<0.05$). Even though N, PS, and PS2 were not significant (P>0.05), all the nutrient variables were retained in the model since they are required for plant growth.

For the 1984 and 1985 data, two nutrient variables (N85 and PS85) were added to the model to capture the difference in nutrient impacts between 1984 and 1985. The complete quadratic model with all data contained many insignificant variables and variables with unexpected signs (Model 2-1, Table 2) and was not acceptable. When the data from the last grazing period in each year was deleted (for the reasons stated earlier), DD, DD2, PS85, DRYPS, and LAGFOR were significant (P<0.05) (Model 2-2). The expected decrease in response to nutrients was found in the negative coefficients on the N85 and PS85 variables.

Partial F-tests in both Models 2-1 and 2-2 showed the moisture variables (DRY, DRY2, DRYN, and DRYPS) were significant (P<0.05) in explaining the variance in forage growth in the 1984 and 1985 grazing seasons and should not be eliminated from the model for statistical reasons. However, DRY and DRY2 had coefficient signs different from expectations. Deleting the four moisture variables decreased the adjusted R^2 slightly (Model 2-3).

Raguse, et al (1988) found the effect of N was not significant in 1984 and 1985. In the current study, a partial F-test of Model 2-3 showed the N variables (N, N2, N85, DDN, DRYN, and NPS) were not significant (P>0.05) in explaining the variance in forage growth in the 1984 and 1985 grazing seasons. The forage growth model was reestimated without the N variables at an equivalent explanatory power (Model 2-4).

Compared to Model 2-4, deleting the lagged forage variable resulted in a much lower adjusted R^2 (Model 2-5). Thus, even though only PS85 and LAGFOR were significant ($P<0.05$), Model 2-4 was selected as the appropriate model of forage growth in the 1984 and 1985 grazing seasons. All coefficient signs are as expected. The impact of the PS level was estimated to be less in 1985 than in 1984 since the PS85 coefficient was negative.

The complete quadratic model with the data from all three years had similar results to the previous models (Model 3-1, Table 3) including the unexpected signs on DD and DD2. However, a partial F-test of Model 3-1 indicated that the hypothesis that the coefficients on the moisture variables (DRY, DRY2, DRYN, and DRYPS) equal 0 should not be rejected ($P<0.01$). Reestimating the model without these variables resulted in a very slight decrease in the adjusted R^2 (Model 3-2).

For reasons stated earlier, the data from the last grazing period in each year was deleted and the model reestimated (Model 3-3). Compared to Model 3-2, DD, DD2, and N were not significant ($P>0.05$) in Model 3-3 although the coefficient on DDN was significant. To be consistent, Model 3-3 was selected over Model 3-2 since the last grazing period was not relevant to the rancher's decision as discussed earlier.

Animal Gain Response. The 1983 response of animal weight gain to fertilization was similar to the response of forage discussed in the previous section. Once again the decision to include the moisture variables has conflicting evidence. As in the forage response models, the moisture variables (DRY and DRY2) in the animal gain response model have impacts opposite that which was expected (Model 4-1, Table 4). That is, the linear response was positive when it was expected to be a negative response to the lack of moisture, as measured by DRY. However, the partial F-test on Model 4-1 indicated the four moisture variables were significant ($P<0.05$). The other coefficients have signs as expected. Excluding the four variables involving DRY resulted in a slightly lower adjusted R^2 (Model 4-2).

When the last grazing period was deleted from the 1983 data, the DRY variable retained its positive, unexpected sign (Model 4-3). Again the partial F-test was significant ($P<0.05$) in the rejection of those coefficients being 0. When the four moisture variables were removed from the model, the adjusted R^2 decreased to .78 (Model 4-4). Deleting the lagged forage variable resulted in a lower R^2 also (Model 4-5). For best explanatory power and fit of biological expectations, Model 4-4 was chosen as the best animal gain model for 1983 data only.

In Model 4-4, the animal gain response in 1983 was estimated to be significantly ($P<0.05$) and positively affected by DD, N, DDPS, NPS, and LAGFOR. DD2 and N2 have significant ($P<0.05$) and negative coefficients as expected. PS, PS2, and DDN were not significant ($P>0.05$) but were retained for model completeness.

To compare the seasonal response with annual data, the Cobb-Douglas functional form for the animal gain model was estimated with 1983 seasonal data only (Model 10-1, Table 10). All of the coefficients in Model 10-1 were significant ($P<.01$).

No model of animal gain data from 1984 and 1985 was acceptable as a model of the agronomic response. DRY and DRY2 had coefficient signs opposite from those expected both with the last grazing period (Model 5-1,

Table 5) and without the last period (Model 5-2). In addition, without the last period, the coefficients for the degree-days and the PS variables also had signs different from expectations. Even though the partial F-tests of the moisture variables (DRY, DRY2, DRYN, and DRYPS) have shown the coefficients to have significant explanatory power in both models, they are eliminated in Model 5-3. Since N was estimated to be either used or leached from the soil after the wet 1983 season (Raguse, et al, 1988), the impact of N, N2, N85, DDN, and NPS were tested by a partial F-test on Model 5-3 which showed that the N variables had an insignificant ($P>0.10$) impact on explaining the variation in animal gain in 1984 and 1985. Excluding the N variables, resulted in a very small change in the adjusted R^2 (Model 5-4). Excluding the lagged forage variable caused a large decrease in the adjusted R^2 (Model 5-5). Since estimated coefficients for the DD and PS variables were in opposition to expectations, Model 5-4 cannot be selected as the best model of the animal gain response in 1984 and 1985. For purely predictive powers, Models 5-1 or 5-2 were better due to their superior explanatory power although they had coefficient signs which deviated from expectations.

The animal gain response model for data from 1983, 1984, and 1985 combined had estimation problems similar to the forage response model. The moisture variables had signs opposite of expectations (Model 6-1, Table 6). The partial F-test on these variables in Model 6-1 showed that they were significantly different from zero but biologically the sign was not correct. Removing these four variables reduced the explanatory power of the model (Model 6-2). Deleting the last grazing period in each of the three periods resulted in a model of similar explanatory power and estimated coefficients (Model 6-3). Over all three years, the degree-days and the lagged forage variables were estimated to have significant impacts on the animal gain. N had significant ($P<0.05$), positive linear impacts which were essentially eliminated by the significant ($P<0.05$), negative coefficients on the annual variables (N84 and N85) for the last two years. The PS variables were not significant ($P>0.05$) except for PS85 which was estimated to have a significant ($P<0.05$), positive effect on animal gain in 1985 (although that positive impact was essentially negated by the coefficient on PS itself). DDPS and NPS were significant ($P<0.05$) also.

The Cobb-Douglas functional form for the animal gain model was estimated also with the combined 1983, 1984, and 1985 seasonal data (Model 10-2, Table 10). All of the coefficients in Model 10-2 were significant ($P<.01$) except for the phosphorus-sulfur variables. The coefficients on LNP and LNP85 are significant ($P<.05$) while the coefficient on LNP84 is not significant ($P>.10$).

Stocking Rate Response. The discovery process for the stocking rate response to fertilization was similar to the processes for forage and animal gain; consequently, this section was shortened. DRY and DRY2 coefficients were estimated with signs different from those expected with all three sets of data (Tables 7, 8, and 9, respectively). Partial F-tests showed that the moisture variables should be included in the models while biological reasoning said that they must be misspecified and thus excluded. The last grazing period was also excluded in some model estimations. Although they were not significant ($P>0.05$), PS and PS2 also had estimated coefficients with signs opposite than expected; this persisted across models and years.

Model 7-4 was selected as the best model of stocking rate response with 1983 data only. DD, DD2, N, N2, DDN, DDPS, NPS, and LAGFOR were significant ($P<0.05$). PS and PS2 are the only variables with coefficient signs different than expected and they were also not significant ($P>0.05$).

For the stocking rate response in 1984 and 1985, there was no model worthy of selection for modeling the agronomic response. All models had signs different from expectations, many insignificant coefficients, and/or low explanatory power. For purely predictive purposes, Models 8-1 or 8-2 had the highest adjusted R^2 with the last grazing period and without the period, respectively.

When all three years were combined, Model 9-3 was selected as the best model considering coefficient signs, significance, and the exclusion of the last grazing period. Significant ($P<0.05$) variables in the three-year stocking rate response were DD, DD2, N, N84, N85, DDN, DDPS, NPS, and LAGFOR. The response to N alone was effectively limited to the first year with the coefficients on N84 and N85 canceling as least part of the N coefficient. PS and PS2 had coefficients with signs different from what were expected.

Modeling response to fertilizer. For various purposes, estimates of the forage growth, animal gain, and stocking rate are needed under different conditions of weather and fertilization. Examples of this are the modeling of scheduling the use and need for forage resources by ranches. The equations estimated above can be used to estimate the responses in different time periods and different ranges which could be used to help decide how many hectares are needed at different times, which areas need to be fertilized, and how much hay needs to be harvested or purchased to meet the needs at certain times.

These equations can be used to model forage growth and animal gain on similar ranges by inserting the data for the degree-days and fertilization variables. However, when estimating the response, the user must remember that the length of time from which the data was obtained. The above equations were estimated from data which were obtained in 3 and 2 week intervals: 3 week intervals in the winter and 2 week intervals in the spring. To estimate the response for a 2 or 3 week period, the data for the degree days and fertilization are used to estimate the response directly. However, to estimate the response for a period of time longer than 2 or 3 weeks, the data must be split into two or more 2 or 3 week intervals, estimated for each interval, and the estimates summed to the total for the longer time period. If the longer time period is not divided, the forage, gain and stocking rate responses may be estimated incorrectly due to the data being larger than the original dataset and/or due to the interaction of the data within a time period which could be lost due to aggregation.

ESTIMATES FROM ANNUAL DATA

In the previous section, the models estimated were for the response on a seasonal basis with the data measured every 2 or 3 weeks. In this section, the data are aggregated to the annual level over weigh periods for each replication and the conceptual model for animal gain is reestimated. This aggregation is done to allow fertilizer recommendations to be made easier and to reflect the actual operation of the ranch which sells a product only once a year versus multiple sale periods within a year. Since most ranches have only one main product to sell (animals); only the animal gain model is estimated.

Annual animal gain response. There are four inputs in the conceptual models: degree-days, moisture, nitrogen, and phosphorus-sulfur levels. Moisture is measured differently for the annual data; the other variables are measured as they were for the seasonal data only as annual totals. Duncan and Woodmansee found that the moisture received in November and April was critical to the total production of the range. Raguse, et al, (1988) found that the November rainfall was not limiting in any of the three years but April was in the latter two years. Consequently, for the annual estimates, the moisture variables are measured as total rainfall during the grazing season and as rainfall during the month of April. Since the moisture variables were removed from consideration in the weigh-period estimations in the previous section, the model is estimated without those variables for comparison.

The response function of animal gain was estimated as a Cobb-Douglas function[3]. The Cobb-Douglas form is:

$$G = AD^bR^cN^dP^e \qquad [5]$$

where G = total animal gain during grazing,

D = total degree days during the grazing season,

R = rainfall during either the entire season or just April,

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[3]The quadratic form was not possible to estimate due to the small number of observations (3 years, 7 treatments, and 2 reps) and insufficient variance in the measurements of the fertilizer treatment levels causing the matrix to be of not full rank.

N = nitrogen level applied at a previous date,

P = phosphorus/sulfur level applied at a previous date, and

A,b,c,d,and e = parameters of the model.

The Cobb-Douglas model [5] was estimated in the log form:

$$\ln G = \ln A + b\ln D + c\ln R + d\ln N + e\ln P \qquad [6]$$

using the data from 1983 only and using the data from all three years. When the data from all three years are used, dummy slope variables for each nutrient are inserted into the equation in the second and third years to estimate the importance of or lack of nutrient carryover to those latter years.

Using 1983 data only, both N and PS treatments are positive and significant ($P<.01$) in explaining differences in total annual forage production (Model 10-3, Table 10). The values of the coefficients in Model 10-3 are very similar in magnitude to the coefficients in the seasonal data (Model 10-1). This is surprising since it is annual data versus seasonal data which is at 2 or 3 week intervals. However, the annual model explains a larger proportion of the variance as shown by its higher adjusted R^2. Also, seasonally, the level of degree-days has a large impact in explaining seasonal forage production (Model 10-1) since the data is collected beginning in the winter and through the spring. The degree-days were not included in Model 10-3 since it was the same value for each treatment in this single year.

Similar results were obtained using annual data from all three years: N and PS levels were significant (Table 10). However, some unexpected results were the lack of significance ($P>.10$) of degree-days and rainfall. Rainfall was insignificant in both its total rainfall and April rainfall measurements (Models 10-4 and 10-5). Signs were also different from expectations. The significance ($P<.01$) of the 1984 N variable and the insignificance ($P>.10$) of the 1983 N variable were different from expectations and from results reported by Raguse, et al. (1988). The significance of the PS variable ($P<.01$) is consistent with Raguse, et al. (1982).

Of these three models (10-4, 5, and 6), there is not a strong choice for best annual model. All three have the same adjusted R^2 and also have insignificant coefficients and signs different from expectations. This lack of significance may be due to only 3 years of data and thus lack of observations.

The annual models also proved to be unacceptable when formulating fertilizer recommendations. The recommendations were formulated from the annual equations (Table 10) following the procedures in Beatte and Taylor (p. 111). The new recommendations deviate from past recommendations, past experimental evidence, and traditional fertilization practices. Also, they did not behave as expected with respect to product price changes. The unacceptability of the recommendations result from a lack of data richness due to only three years of data collection, one fertilizer application date, and only two fertilization levels (above zero).

SUMMARY

Over all estimated models using seasonal data, several points were observed. First, the weather variables, the interaction variables, and the lagged forage variable were significant in explaining forage growth, animal gain, and stocking rate. Second, the moisture (that is, the lack-of-moisture) variable while usually significant had a coefficient with a sign different than expected. Thus, biologically, the moisture variable must have been misspecified; since other moisture variables were considered when the conceptual model was developed, the search for the appropriate moisture variable continues. Third, N was significant in the first year but not in the second and third years. Fourth, the impact of PS was more important in interaction with another variable (e.g., DD or N) than by itself. Lastly, the correct model for 1984 and 1985 data combined was difficult to find (if it was found) due to the inability of even DD to consistently explain variations in forage growth, animal gain, and stocking rate.

Using annual data for the animal gain model, the weather variables are not significant; both rainfall and degree-days also have signs different from expectations. N and PS variables do have significant impacts on animal gain. The 1984 variable for N is significant while the N overall 3 years is not. P for all 3 years is significant but the separate P variables for 1984 and 1985 are not. These models of annual animal gain are deemed unsatisfactory in present specification as a result of a lack of data richness.

Table 1. Parameters and t-statistics for forage response model using 1983 data only

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	PS	PS2	DDN
1-1	COMPLETE FORAGE with last date	.7630	603.358 .832	16.5930** 2.5340	-.0372** -2.3200	282.2840** 2.3680	-2.6500** -2.3340	9.9360 .4830	-.4380* -1.8450	8.7900 .2590	-.6420 -1.1580	.1771*** 3.7720
1-2	REDUCED FORAGE with last date	.7330	-385.343 -.653	14.9470*** 4.5220	-.0176*** -4.5690			39.8060** 2.0040	-.4640* -1.8420	34.2180 1.0340	-.7060 -1.2000	.0322 1.3630
1-3	COMPLETE FORAGE w/o last date	.7908	444.2206 .6050	16.2382** 2.4590	-.0350** -2.1970	166.1112* 1.7350		13.4100 .6220	-.4644* -1.8470	9.0754 .2550	-.6092 -1.0360	.1476*** 2.9880
1-4	REDUCED FORAGE w/o last date	.7890	442.659 .747	10.2380*** 3.0720	-.0130*** -3.0280			23.4430 1.1640	-.4690** -1.8590	14.9860 .4480	-.6210 -1.0530	.0965*** 3.2320
1-5	REDUCED FORAGE w/o last date & lag	.7307	610.214 .968	18.2960*** 5.5150	-.0206*** -4.4670			18.1515 .8030	-.3850 -1.3460	5.5393 .1470	-.4154 -.6210	.1304*** 3.9840

(cont'd.)

EQN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0
1-1	.1850** 2.5360	-1.8900*** -3.4890	-1.4130* -1.6830	.8380** 2.3630	.3170*** 4.9120	Reject
1-2	.0751** 2.0050			.7458** 1.9870	.3910*** 5.9410	
1-3	.1583** 2.0490	-1.0359 -1.2820	-.5462 -.4260	.9984*** 2.6550	.3677*** 5.3500	Do Not Reject
1-4	.1312*** 2.8260			.9778** 2.5910	.3850*** 5.6310	
1-5	.1415*** 2.7210			1.3680*** 3.2570		

* 10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 2. Parameters and t-statistics for forage response model using 1984 & 1985 data

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	N85	PS	PS2 (cont'd.)
2-1	COMPLETE FORAGE	.881	344.574	.555	-2.532e-3	5.154	.052	-6.915	0.090	-6.836**	1.385	-0.034
	with last date		1.426	.296	-.852	.434	.322	-0.837	0.881	-2.030	0.102	-0.144
2-2	REDUCED FORAGE	.880	103.486	1.874	-3.931e-3			-7.735	0.100	-2.633	1.289	-0.100
	w/o last date		.483	.999	-1.100			-1.023	1.049	-0.879	0.104	-0.453
2-3	COMPLETE FORAGE	.888	112.476	3.840**	-.011***	34.676*	-.375	-5.475	0.074	-5.562*	3.178	-0.071
	w/o last date		.530	1.994	-2.702	1.955	-1.313	-0.746	0.808	-1.806	0.264	-0.332
2-4	REDUCED FORAGE	.881	3.806	2.002	-4.114e-3						2.733	-0.100
	w/o last date & N		.021	1.098	-1.160						0.307	-0.630
2-5	REDUCED FORAGE	.478	-244.827	19.275***	-.035***			17.904	-0.086	-35.390***	8.159	0.078
	w/o last date & lag		-.554	5.273	-4.919			1.153	-0.435	-6.237	0.318	0.169

EQN	PS85	DDN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0	Ho: N=0
2-1	-16.614***	.012	.013	-.033	.340	.121	.809***	Reject	
	-3.037	.605	.426	-.248	1.617	.807	21.415		
2-2	-9.935**	3.1045e-3	.034*			.057	.898***		
	-2.024	.248	1.662			.405	26.436		
2-3	-10.440**	.010	5.4790e-4	-.070	.431**	.075	.769***		Do Not Reject
	-2.116	.618	.020	-.541	2.111	.553	16.493		
2-4	-10.293**		.033*				.908***	Reject	
	-2.114		1.664				29.654		
2-5	-61.944***	.016	.100**			.157			
	-6.619	.600	2.399			.541			

* 10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 3. Parameters and t-statistics for forage response model using 1983-85 data

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	N84	N85	PS	PS2	PS84
3-1	COMPLETE FORAGE with last date	.845	269.086 1.029	2.795* 1.781	-5.452e-3*** -2.716	4.148 .337	.130 .857	21.265** 2.051	-.141 -1.187	-16.230*** -3.187	-29.173*** -5.650	19.312 1.166	-.299 -1.082	-8.540 -1.144
3-2	REDUCED FORAGE with last date	.844	219.340 .876	2.930** 2.087	-4.050e-3** -2.140			22.855** 2.323	-.140 -1.182	-16.022*** -3.685	-28.491*** -5.828	15.788 .993	-.304 -1.094	-3.066 -.477
3-3	REDUCED FORAGE w/o last date	.855	314.946 1.234	2.280 1.399	-4.257e-3 -1.649			19.508* 1.962	-.140 -1.175	-16.913*** -3.781	-27.284*** -5.487	13.820 .859	-.313 -1.123	-6.765 -1.043

(cont'd.)

EQN	PS85	DDN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0
3-1	-39.307*** -5.259	.032 1.591	.066** 2.131	-.168 -1.077	.045 .184	.242 1.385	.687*** 21.436	Do Not Reject
3-2	-35.579*** -5.023	.015 1.286	.071*** 3.768			.237 1.355	.695*** 21.788	
3-3	-32.958*** -4.645	.029** 1.956	.084*** 3.561			.261 1.481	.719*** 21.617	

* 10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 4. Parameters and t-statistics for gain response model using 1983 data only

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	PS	PS2	DDN (cont'd.)
4-1	COMPLETE GAIN	.8460	-3.6660*	.1270***	-2.9e-4***	1.8150***	-.0181***	.1690***	-.0020***	.0190	-.0002	3.56e-4***
	with last date		-1.9610	7.5130	-7.0900	5.9020	-6.1800	3.1850	-3.3120	.2170	-.1490	2.9380
4-2	REDUCED GAIN	.7690	-5.6080***	.0885***	-1.33e-4***			.2760***	-.0021***	.0960	-4.78e-4	-1.69e-4**
	with last date		-3.1910	8.9970	-11.6050			4.6690	-2.8500	.9750	-.2730	-2.4100
4-3	COMPLETE GAIN	.8389	-3.4044*	.1214***	-2.859e-4***	1.3243***		.1657***	-.0022***	.0113	-1.149e-4	3.8295e-4***
	w/o last date		-1.8280	7.2580	-7.0740	5.4600		3.0320	-3.4760	.1250	-.0770	3.0590
4-4	REDUCED GAIN	.7820	-3.1851*	.0716***	-1.08e-4***			.2467***	-.0023***	.0462	-2.1e-4	-3.1e-5
	w/o last date		-1.8320	7.3230	-8.5010			4.1760	-3.0420	.4700	-.1220	-.3590
4-5	REDUCED GAIN	.7219	-2.1059	.0928***	-1.276e-4***			.2229***	-.0020**	.0053	4.7577e-4	8.1466e-5
	w/o last date & lag		-1.1380	9.5300	-9.4310			3.3570	-2.3510	.0480	.2420	.8480

EQN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho:DRY=0
4-1	4.55e-4**	-.0069***	-.0041*	.0019**	8.26e-4***	Reject
	2.4220	-4.9080	-1.9030	2.0700	4.9700	
4-2	1.35e-4			.0015	.0012***	
	1.2120			1.3400	5.9750	
4-3	4.232e-4**	-.0084***	-.0031	.0023**	.0010***	Reject
	2.1620	-4.1040	-.9470	2.4580	5.6490	
4-4	2.68e-4**			.0022**	.0011***	
	1.9700			1.9670	5.6050	
4-5	3.201e-4**			.0034***		
	2.0970			2.7590		

* 10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 5. Parameters and t-statistics for gain response model using 1984 & 1985 data

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	N85	PS	PS2	PS85	DDN
5-1	COMPLETE GAIN	.641	4.577***	.028***	-4.141e-5**	.696***	-.010***	.024	-6.464e-4	3.0490e-3	-.097	2.2032e-3	.109***	3.4017e-5
	with last dat		3.318	2.598	-2.441	10.275	-10.879	.507	-1.104	.159	-1.250	1.617	3.478	.305
5-2	REDUCED GAIN	.630	6.466***	-.022*	1.0928e-4***			.0149e-3	-2.809e-4	.034	-.145*	1.8658e-3	.083**	-7.479e-5
	w/o last date		4.429	-1.722	4.491			.097	-.434	1.645	-1.711	1.236	2.495	-.877
5-3	COMPLETE GAIN	.715	6.681***	-3.839e-3	5.0135e-5**	.186*	-5.273e-4	.031	-5.579e-4	-3.114e-3	-.117	2.1603e-3	.077**	1.8179e-5
	w/o last date		5.085	-.322	2.004	1.693	-.298	.685	-.980	-.163	-1.576	1.631	2.517	.176
5-4	REDUCED GAIN	.629	6.813***	-.025**	1.1176e-4***						-.063	3.7384e-4	.087**	
	w/o last date & N		5.461	-1.975	4.593						-1.032	.343	2.597	
5-5	REDUCED GAIN	.524	5.704***	.013	4.794e-5*			.058	-6.639e-4	-.033	-.128	2.2008e-3	-.022	-5.153e-5
	w/o last date & lag		3.492	.965	1.845			1.019	-.911	-1.553	-1.347	1.292	-.625	-.536

(cont'd.)

EQN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0	Ho: N=0
5-1	-2.346e-4	-3.209e-4	3.2058e-3***	1.7458e-3**	2.5706e-4	Reject	
	-1.306	-.423	2.673	2.035	1.192		
5-2	3.1732e-4**			1.3740e-3	1.8111e-3***		
	2.292			1.445	7.829		
5-3	-1.030e-4	-9.036e-4	5.3842e-3***	1.5484e-3*	4.3174e-4		Do Not Reject
	-.618	-1.121	4.261	1.855	1.497		
5-4	3.3402e-4**				1.6656e-3***	Reject	
	2.443				7.925		
5-5	4.4878e-4***			1.5513e-3			
	2.898			1.449			

* 10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 6. Parameters and t-statistics for gain response model using 1983-85 data

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	N84	N85	PS	PS2	PS84 (cont'd.)
6-1	COMPLETE GAIN with last date	.640	-28.299 -.766	2.718*** 12.260	-4.841e-3*** -17.083	15.619*** 8.983	-.186*** -8.659	5.180*** 3.539	-.033** -1.994	-3.671*** -5.105	-2.659*** -3.647	-.419 -.179	.045 1.148	-2.972 -2.820
6-2	REDUCED GAIN with last date	.545	-75.156* -1.896	3.211*** 14.453	-4.795e-3*** -16.014			5.213*** 3.348	-.034* -1.804	-3.229*** -4.693	-2.229*** -2.882	-1.827 -.726	.044 .994	-1.012 -0.995
6-3	REDUCED GAIN w/o last date	.592	16.532 .404	2.095*** 8.018	-2.652e-3*** -6.409			4.820*** 3.025	-.034* -1.791	-3.070*** -4.283	-2.119*** -2.660	-3.898 -1.512	.045 1.017	0.804 0.774

EQN	PS85	DDN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0
6-1	1.507 1.428	6.2553e-4 .223	2.7235e-3 .625	-.026 -1.168	.031 .893	.059** 2.409	.024*** 5.361	Reject
6-2	2.881** 2.570	-1.696e-3 -.898	6.1296e-3** 2.050			.058** 2.101	.024*** 4.716	
6-3	3.129*** 2.752	-4.117e-4 -.172	.013*** 3.369			.061** 2.144	.028*** 5.341	

* 10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 7. Parameters and t-statistics for stocking rate response model using 1983 data only

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	PS	PS2	DDN
7-1	COMPLETE RATE with last date	.8430	.0266* 1.7180	.0010*** 6.8120	-2.5e-6*** -7.4100	.0173*** 6.7970	-1.25e-4*** -5.1780	7.05e-4 1.6060	-1.72e-5*** -3.3980	-6.96e-4 -.9630	5.5e-6 .4650	5.3e-6*** 5.2600
7-2	REDUCED RATE with last date	.7620	.0204 1.3910	4.3e-4*** 5.2100	-5.8e-7*** -6.1420			1.62e-3*** 3.2900	-1.8e-5*** -2.8810	1.3e-4 .1590	3.6e-6 .2470	7.6E-07 1.2900
7-3	COMPLETE RATE w/o last date	.8668	.0234 1.5110	.0010*** 6.8770	-2.509e-6*** -7.4550	.0129*** 6.4100		7.442e-4 1.6360	-1.749e-5*** -3.2970	-6.292e-4 -.8370	3.8940e-6 .3140	4.5630e-6*** 4.3780
7-4	REDUCED RATE w/o last date	.8150	.0414*** 2.8250	3.44e-4*** 4.1700	-5.7e-7*** -5.3000			1.09e-3** 2.1930	-1.8e-5*** -2.8420	-3.06e-4 -.3690	3.3e-6 .2240	2.7e-6*** 3.6950
7-5	REDUCED RATE w/o last date & lag	.7462	.0490*** 3.0330	5.595e-4*** 6.5880	-7.681e-7*** -6.5090			9.035e-4 1.5600	-1.522e-5** -2.0780	-6.356e-4 -.6600	9.4823e-6 .5540	3.7506e-6*** 4.4760

(cont'd.)

EQN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0
7-1	4.6e-6*** 2.9300	-5.9e-5*** -5.1200	-4.81e-5*** -2.6840	3.1e-5*** 4.1130	8.94e-6*** 6.4990	Reject
7-2	8.8E-07 .9430			2.8e-5*** 3.0340	1.1e-5*** 7.0220	
7-3	4.088e-6** 2.5080	-3.651e-5** -2.1410	-3.257e-5 -1.2050	3.678e-5*** 4.6350	9.611e-6*** 6.6270	Reject
7-4	2.5e-6** 2.1940			3.6e-5*** 3.8100	1.08e-5*** 6.4060	
7-5	2.914e-6** 2.1890			4.696e-5*** 4.3670		

* 10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 8. Parameters and t-statistics for stocking rate response model using 1984 & 1985 data

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	N85	PS	PS2	PS85	DDN (cont'd.)
8-1	COMPLETE HERD with last dat	.784	.088***	3.0715e-4***	-5.350e-7***	4.0164e-3***	-2.130e-5***	6.4495e-4*	-1.275e-5***	6.5218e-5	-1.033e-3*	2.2395e-5**	1.6019e-4	3.8603e-7
			8.350	3.747	-4.121	7.745	-3.037	1.787	-2.845	.443	-1.748	2.148	.670	.452
8-2	REDUCED HERD w/o last date	.488	8.090e-2***	7.694e-5	3.7316e-7			1.1362e-4	-5.598e-6	4.9166e-4**	-9.384e-4	1.0979e-5	4.3106e-4	-2.746e-7
			5.770	.627	1.597			.230	-.901	2.511	-1.157	.758	1.343	-.335
8-3	COMPLETE HERD w/o last date	.737	8.642e-2***	3.4062e-4***	-6.457e-7***	4.6227e-3***	-3.377e-5**	5.1652e-4	-9.823e-6**	5.6148e-5	-7.457e-4	1.5715e-5	1.4182e-4	3.4638e-7
			8.383	3.642	-3.290	5.368	-2.433	1.450	-2.200	.375	-1.277	1.512	.592	.427
8-4	REDUCED HERD w/o last date & N	.482	8.391e-2***	6.4491e-5	4.0633e-7*			-5.294e-4	3.4688e-6	4.7930e-4				
			6.969	.534	1.730			-.899	.330	1.486				
8-5	REDUCED HERD w/o last date & lag	.452	7.699e-2***	2.5258e-4**	6.639e-8			3.7016e-4	-7.422e-6	1.6815e-4	-8.658e-4	1.2768e-5	-8.251e-5	-1.720e-7
			5.380	2.133	.292			.736	-1.162	.915	-1.041	.855	-.272	-.204

EQN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0	Ho: N=0
8-1	-9.904e-7	-2.608e-6	3.911e-5***	1.3781e-5**	-1.202e-5***	Reject	
	-.720	-.449	4.262	2.099	-7.282		
8-2	2.3003e-6*			6.3774e-6	8.8858e-6***		
	1.730			.699	4.000		
8-3	-7.764e-7	-5.231e-6	4.5174e-5***	9.2517e-6	-1.248e-5***		Do Not Reject
	-.594	-.827	4.557	1.413	-5.516		
8-4	2.3351e-6*				6.7262e-6***	Reject	
	1.769				3.316		
8-5	2.9264e-6**			7.3922e-6			
	2.157			.788			

*   10% Significance Level
** 5% Significance Level
*** 1% Significance Level

Table 9. Parameters and t-statistics for stocking rate response model using 1983-85 data

EQN	MODEL	adj. R**2	Int'cpt	DD	DD2	DRY	DRY2	N	N2	N84	N85	PS	PS2	PS84
9-1	COMPLETE HERD with last date	.683	16.402*** 5.170	.185*** 9.732	-3.105e-4*** -12.754	.846*** 5.665	-2.307e-3 -1.254	.490*** 3.897	-3.667e-3** -2.554	-.480*** -7.771	-.290*** -4.629	-.086 -.429	5.361e-3 1.596	-.365*** -4.037
9-2	REDUCED HERD with last date	.530	14.227*** 3.858	.192*** 9.294	-2.185e-4*** -7.843			.423*** 2.917	-3.667e-3** -2.098	-.339*** -5.291	-.161** -2.235	-.414* -1.766	5.085e-3 1.244	.051 .543
9-3	REDUCED HERD w/o last date	.574	19.158*** 5.368	.136*** 5.970	-1.633e-4*** -4.523			.335** 2.408	-3.175e-3* -1.903	-.331*** -5.290	-.165** -2.372	-.306 -1.362	3.196e-3 .819	5.780e-3 -.064

(cont'd.)

EQN	PS85	DDN	DDPS	DRYN	DRYPS	NPS	LAGFOR	Ho: DRY=0
9-1	2.436e-4 .003	4.5714e-4** 1.894	-4.043e-5 -.108	-3.180e-3** -1.678	8.385e-3*** 2.816	6.886e-3*** 3.250	6.955e-4* 1.791	Reject
9-2	2.887e-1*** 2.768	1.9666e-4 1.119	8.5085e-4*** 3.058			6.583e-3** 2.552	1.161e-3** 2.473	
9-3	.183* 1.842	4.6541e-4** 2.230	9.7294e-4*** 2.946			5.924e-3** 2.405	2.089e-3*** 4.488	

* 10% Significançe Level
** 5% Significance Level
*** 1% Significance Level

Table 10. Parameters and t-statistics for the animal gain model using the Cobb-Douglas functional form.

EQN	MODEL	adj. R**2	LNA	LNDD	LNR	LNRA	LNN	LNN84	LNN85	LNPS	LNPS84	LNPS85
SEASONAL DATA												
10-1	1983 data only	.76	2.963*** (16.25)	.522*** (15.94)			.555*** (8.98)			.41*** (5.87)		
10-2	1983-1985 data	.51	3.308*** (20.76)	.472*** (15.95)			.556*** (7.04)	-.491*** (-4.79)	-.58*** (-5.76)	.193** (2.29)	.029 (0.26)	.245** (2.14)
ANNUAL DATA												
10-3	1983 data only	.92	4.29*** (102.90)				.584*** (11.42)			.44*** (7.63)		
10-4	1983-1985 data with total rainfall	.78	9.388*** (4.35)	-.167 (-0.52)	-.055 (-0.45)		-.011 (-0.17)	.595*** (6.41)	.02 (0.22)	.275*** (3.71)	.165 (1.57)	-.03 (-0.29)
10-5	1983-1985 data with April rainfall	.78	9.381*** (4.33)	-.192 (-0.66)		-.011 (-0.45)	-.011 (-0.17)	.595*** (6.41)	.02 (0.22)	.275*** (3.71)	.165 (1.57)	-.03 (-0.29)
10-6	1983-1985 data without rainfall	.78	9.927*** (5.60)	-.265 (-1.11)			.0032 (0.06)	.576*** (7.03)	-.004 (-0.05)	.264*** (3.83)	.171 (1.67)	-.003 (-0.03)

* 10% significance level
** 5% significance level
*** 1% significance level

APPENDIX

Another set of model estimates specified the three conceptual models of forage growth [2], animal gain [3], and stocking rate [4] in three functional forms: linear, quadratic, and square-root. These models were estimated using two sets of data: (1) the combined data for 1983, 1984, and 1985 and (2) the 1983 data only. The data were in English, not metric, measurements.

The variables used are:

Weather variables:

DD	= degree-day units per period
DD2	= DD squared
DDRT	= Square root of DD
DRY	= number of days in each period after the summer dry season has begun
DRY2	= DRYDAY squared
DRYRT	= square root of DRYDAY

Nutrient variables:

N	= N treatment level
N2	= N squared
NRT	= square root of N
N84	= N in 1984, 1983 & 1985 = 0
N85	= N in 1985, 1983 & 1984 = 0
PS	= P treatment level (which was proportional to the S treatment level)
PS2	= PS squared
PSRT	= square-root of PS
PS84	= PS in 1984, 1983 & 1985 = 0
PS85	= P in 1985, 1983 & 1984 = 0

Weather and nutrient interaction variables:

DDN	= DD * N
DDPS	= DD * PS
DRYN	= DRY * N
DRYPS	= DRY * PS
NPS	= N * PS

Lagged response variable:

LAGFOR	= forage lagged one period

The interaction between DD and DRY was excluded in this analysis because the matrix was not of full rank when it was included.

Forage response. The linear form of the forage response model has a higher adjusted R^2 compared to the quadratic and square root functional forms (Table A1). However, we would expect the response to be curvilinear with some point of diminishing response, as allowed by both quadratic and square root functional forms. The quadratic form was chosen as the best of the three because of its curvilinear form and the significance of critical variables (specifically the nitrogen variables) compared to the square root form.

The quadratic form shows these variables to be significant at a 5% level: DD, DD2, N, N84, N85, PS85, DDN, DRYN, and NPS. The quadratic term for N (N2) was not significant (P>.20) but was accepted because of the need for a curvilinear response. Only the PS variable for 1985 was significant. This contradicts the earlier work showing a soil test deficiency for P and S (Raguse, et al, 1988). However, the interaction between the N and PS levels was significant. The square-root form gave the same results except that the N response was not significant (P>0.05).

The forage response to the lack of moisture variable (DRY) was not significant (P>0.05) and had the wrong sign. Plots of forage growth versus DRY show a positive relationship when a negative relationship was expected. The onset of the dry season may have been later that assumed in the formulation of the DRYDAY variable indicating that the definition of the moisture variable requires additional refinement.

Animal Gain Response. The quadratic functional form of the animal gain model was superior to the linear and square-root forms in terms of both the adjusted R^2 and the significance of individual variables (Table A2). In the quadratic form, these variables were significant (P>0.05): DD, DD2, DRY, DRY2, N, N2, N84, N85, DRYN, and NPS. DRY and DRY2 have signs which are opposite from expectations. The other PS variables were not significant in any of the functional forms for animal gain.

Stocking Rate Response. The coefficients for the stocking rate response model were similar to those of the animal gain response model. The quadratic functional form was chosen over the linear and square-root forms due to its curvilinear form and higher adjusted R^2 (Table A3). The variables which were significant (P>0.05) were: DD, DD2, DRY, DRY2, N, N2, N84, N85, DDN, DRYN, and NPS. Although the signs of DRY and DRY2 differ from expectations.

Results With 1983 Data Only. The first year of the experiment was of above normal precipitation. This probably caused more N to be used in plant growth or leached away. To analyze the impact of this, the three conceptual models were estimated using only 1983 data and the quadratic functional form (Table A4).

Qualitatively, the 1983 data show the same results as using 3 years of data. DD, DD2, N, and N2 were significant (P>0.05) with the expected signs. DRY and DRY2 were significant (P>0.05) but had signs opposite of what was expected. The PS variables are not significant. All of the interaction terms are significant. The forage available at the end of the previous period had a significant coefficient in all three models.

Table A1. Parameter Estimates and T-Statistics for the Forage Model with Combined Data (measured in English units).

Variable	Functional Form Linear	Quadratic	Square Root
Adj. R^2	.838	.726	.723
Intercept	-105.06(-.44)	266.24(0.3)	-4,360(-1.43)
DD	1.32(1.85)	7.24(2.62)	-14.13(-3.87)
DD2		-0.014(-4.62)	
DDRT			386.49(4.32)
DRY	9.76(1.80)	41.81(1.90)	59.55(2.52)
DRY2		0.282(1.26)	
DRYRT			13.21(0.09)
N	757.97(6.01)	2,156.22(2.35)	-1,118.5(-.64)
N2		-285.04(-1.28)	
NRT			5,915.1(1.27)
N84	-425.71(-3.41)	-1,097.05(-6.46)	-1,144.5(-6.57)
N85	-905.83(-6.32)	-2,562.41(-17.32)	-2,572.5(-17.20)
PS	23.43(4.37)	-4.25(-0.15)	-13.21(-.45)
PS2		-0.056(-0.17)	
PSRT			42.21(.17)
PS84	-3.94(-0.53)	-6.83(-0.62)	-6.63(-.60)
PS85	-26.00(-3.47)	-61.18(-6.14)	-59.16(-5.92)
DDN		2.67(2.69)	2.59(2.59)
DDPS		0.079(1.88)	0.080(1.88)
DRYN		-18.47(-2.37)	-17.84(-2.28)
DRYPS		0.12(0.35)	0.113(.33)
NPS		19.56(2.31)	19.56(2.30)
LAGFOR	0.66 (18.29)		

Table A2. Parameter Estimates and T-Statistics for the Animal Gain Model with Combined Data (measured in English units).

Variable	Functional Form Linear	 Quadratic	 Square Root
Adj. R^2	.221	.616	.528
Intercept	194.30(4.01)	-166.80(-1.71)	-1,279(-3.46)
DD	0.127(0.88)	3.04(10.02)	-5.49(-12.41)
DD2		-0.0057(-17.59)	
DDRT			148.77(13.71)
DRY	-.827(-0.75)	20.96(8.68)	-12.00(-4.19)
DRY2		-.200(-8.122)	
DRYRT			165.15(9.48)
N	54.61(2.13)	302.78(3.00)	-270.6(-1.28)
N2		-51.53(-2.10)	
NRT			1,069.4(1.90)
N84	-42.73(-1.69)	-121.74(-6.53)	-157.72(-7.46)
N85	12.94(0.44)	-119.88(-7.38)	-130.12(-7.17)
PS	1.47(1.35)	-3.72(-1.17)	2.84(0.81)
PS2		0.046(1.24)	
PSRT			-34.30(-1.12)
PS84	0.15(0.10)	-1.53(-1.26)	-1.71(-1.27)
PS85	4.78(3.14)	.99(.90)	1.87(1.54)
DDN		0.142(1.30)	0.08(.69)
DDPS		.005(1.10)	0.005(.95)
DRYN		-1.98(-2.32)	-1.50(-1.58)
DRYPS		0.018(0.49)	0.019(0.46)
NPS		2.49(2.68)	2.49(2.42)
LAGFOR	0.041(5.59)		

Table A3. Parameter Estimates and T-Statistics for the Stocking Rate Model with Combined Data (measured in English units).

Variable	Functional Form Linear	 Quadratic	 Square Root
Adj. R2	.510	.687	.661
Intercept	6.10(7.89)	1.88(1.06)	-19.21 (-3.04)
DD	0.002(0.72)	0.037(6.70)	-.086(-11.32)
DD2		-.00008(-13.50)	
DDRT			2.229(12.02)
DRY	0.135(7.64)	.298(6.79)	.198(4.05)
DRY2		-0.0005(-1.15)	
DRYRT			.57(1.92)
N	2.034(4.97)	5.649(3.08)	-7.85(-2.17)
N2		-1.179(-2.65)	
NRT			24.47(2.54)
N84	-2.37(-5.85)	-3.001(-8.85)	-3.30(-9.13)
N85	-0.36(-0.78)	-1.730(-5.86)	-1.76(-5.69)
PS	0.03(1.67)	-0.105(-1.81)	0.05(.84)
PS2		.0011(1.62)	
PSRT			-0.82(-1.56)
PS84	0.007(0.28)	-0.036(-1.61)	-0.03(-1.49)
PS85	0.064(2.64)	0.006(.30)	0.02(0.95)
DDN		0.0067(3.37)	0.0062(3.01)
DDPS		0.0001(0.73)	0.00007(0.74)
DRYN		-0.049(-3.18)	-0.046(-2.81)
DRYPS		0.001(1.95)	0.0013(1.81)
NPS		0.057(3.39)	0.057(3.25)
LAGFOR	0.0005(4.21)		

Table A4. Parameter Estimates and T-Statistics for the Forage, Animal Gain, and Stocking Rate Models Using the Quadratic Functional Form and Only 1983 Data (measured in English units).

Variable	Model: Forage	Model: Animal Gain	Model: Stocking Rate
Adj. R^2	.763	.846	.843
Intercept	678(.83)	-135.9(-1.96)	2.17(1.72)
DD	18.64(2.53)	4.71(7.51)	0.078(6.81)
DD2	-.042(-2.32)	-0.011(-7.09)	-0.00021(-7.41)
DRY	317.17(2.37)	67.30(5.90)	1.410(6.80)
DRY2	-2.98(-2.33)	-0.671(-6.18)	-0.010(-5.18)
N	9.94(0.48)	5.58(3.19)	0.051(1.61)
N2	-.39(-1.85)	0.060(-3.31)	-0.0011(-3.40)
PS	8.79(0.26)	0.63(0.22)	-0.051(-0.96)
PS2	-0.57(-1.16)	-0.006(-0.15)	0.0004(0.47)
DDN	0.177(3.77)	0.012(2.94)	0.00038(5.26)
DDPS	0.185(2.54)	0.015(2.42)	0.00033(2.93)
DRYN	-1.890(-3.49)	-0.226(-4.91)	-0.0043(-5.12)
DRYPS	-1.41(-1.68)	-0.136(-1.90)	-0.0035(-2.68)
NPS	.746(2.36)	0.056(2.07)	0.0020(4.113)
LAGFOR	0.317(4.91)	0.027(4.97)	0.00065(6.50)

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