Potential Climate Change Effects on Warm-Season Livestock Production in the Great Plains

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ABSTRACT

Climate changes suggested by some global climate models (GCM) may impact the economic viability of livestock production systems in the Great Plains region of the United States. Increased ambient temperatures lead to depressed voluntary feed intake (VFI), reduced weight gains, and lower milk production during summer periods. Animals are somewhat able to adapt to higher temperatures with prolonged exposure but production losses will occur in response to higher temperature events. This report presents the potential impacts of climatic change on the VFI of swine and confined beef cattle and the VFI and milk production of dairy cattle. Animal production-response algorithms from research results are combined with climatological data and GCM output to assess potential impacts. Algorithms used are based on the most recent National Research Council publications on the Nutrient Requirements of Swine, Beef Cattle and Dairy Cattle and related publications. Geographic variations in the relative change in temperature and other climate variables associated with two GCM scenarios are identified for the Missouri, Iowa, Nebraska, Kansas region and linked to potential impacts on livestock production. Detailed analyses project economic losses for these livestock classes to increase in most areas during the summer period, in some cases quite markedly. Exploration of the effects of climate changes on livestock should allow producers to adjust management strategies to reduce the potential economic losses due to environmental changes.

KEYWORDS: climate change, livestock production, heat stress, cattle, swine

INTRODUCTION

Increased combustion of fossil fuels since the industrial revolution has elevated atmospheric CO_2 levels by about 30 percent (IPCC, 1995). The potential impacts of such changes in CO_2 levels on global climate are widespread (IPCC, 1996). Global-average surface temperature may rise by 1.5 to 5°C with a doubling of the level of atmospheric CO_2 (IPCC, 1995; MacCracken *et al.*, 2003). In addition to changes in global-average temperature, modeling results suggest an increased likelihood of heat wave events. An increase of 1.4°C in the mean temperature increases by three times the likelihood of an event of 5 or more days with temperatures greater than 35°C in the U.S. Corn Belt (Mearns *et al.,* 1984). Climate change, whether the result of anthropogenic activities or not, will impact agricultural production throughout the world.

Potential direct and indirect impacts of climate change on livestock production have not been thoroughly explored. Changes in crop availability and quality, which have been the primary focus of previous studies (e.g., McGregor, 1993; Easterling *et al.*, 1993), affect animal production through changes in feed supplies. Analyses of direct impacts of climate change on livestock production are few. Using projected global change models, Hahn *et al.* (1992) and Klinedinst *et al.* (1993) found that changes in climate would directly lead to reductions in summer season milk production and conception rates in dairy cows in the United States. Hahn *et al.* (1992) also estimated significant reductions in growth rates of swine during the summer season.

Many environmental factors affect the rates and mechanisms of heat exchange between the animal and its surroundings (McDowell, 1974). The optimal zone for production is a range of temperatures for which the animal does not need to significantly alter behavior or physiological functions to maintain a constant core body temperature. Air temperature is the most important environmental determinant of the zone of optimal production, but changes in the level of insolation, wind, or humidity can change the boundaries of this zone because they alter the heat exchange between the animal and the environment (Johnson, 1965).

Because voluntary feed intake (VFI) is the primary factor influencing the production capacity of livestock, accurate prediction of the feed consumption of livestock under heat stress is a precursor to accurate assessment of changes in production resulting from changes to a warmer climate. Intake models must also consider other factors that affect VFI. The animal's breed, age, and sex affect its maintenance energy requirements and therefore its VFI (NRC, 1996). Management practices, like bunk location and size and feeding frequency also affect feeding behavior (Stricklin, 1986; Laudert, 1995). The health of an animal will affect VFI, as diseased animals will reduce intake (Gaylean and Hubbert, 1995). Water restriction also leads to reduced VFI (Shirley, 1985).

The goal of this study is to explore the relationship between livestock and the environment and the impacts of potential climate change on livestock production in the United States. In particular, warm-season responses of swine, confined beef cattle and dairy cattle are considered through the use of mathematical models to quantify daily animal response in terms of VFI and milk production to changes in climate. Data from a general circulation model (GCM) are input to the animal models to generate an output scenario representative of potential impacts of climate change on the length of time needed to reach slaughter weight and on warm-season milk production in the study area. For the purposes of this study, an animal was identified and variables such as age, weight, and management practices were held constant as climate data were varied to isolate the effects of changes in climate on production.

METHODS

Animal production-response models

Production/response models for growing swine and beef cattle, and milk-producing dairy cattle, were developed based on summary information contained in the most recent National Research Council publications outlining the nutrient requirements of the respective animals (NRC, 1989; NRC, 1996; NRC, 1998) and the predicted feed intake of food animals (NRC, 1987). The goal in the development of these production/response models was to incorporate input of climate variables, primarily an average daily temperature, to generate an estimate of direct, climate-induced changes in daily VFI. Based on daily VFI, estimates of production output (daily body weight gain or daily milk produced) can then be determined. Model development is detailed in Frank *et al*. 2001. Output data from GCM scenarios, discussed in subsequent sections, served as climate inputs to these models.

The swine production model is valid for animals with a body weight between 20 and 120 kg (NRC, 1998) exposed to temperatures in a range of 5 to 40°C. For the purposes of this study, animals were grown from 50 to 110 kg, with average daily temperatures above 20°C. The swine production model involves a series of concatenated calculations based on the known variables of body weight (BW, kg) and mean daily air temperature (T, °C) (figure 1). The net result is an ability to calculate animal production (body weight gain) on a daily basis as a function of thermal conditions.

A 600 kg cow with an average daily 4% milkfat milk production of 30 kg provides the baseline daily voluntary dry matter intake (DMI) (kg) value of 20.69 kg/day (NRC, 1989) for the dairy production model. Adjustments to this daily voluntary DMI are made to account for the effects of temperature, relative humidity, and wind speed. Figure 2 is a flow chart that summarizes the steps involved in the mathematical modeling of biometeorological effects on milk production. The net result is an ability to calculate animal production (fat corrected milk (FCM)) on a daily basis as a function of climatic conditions.

The beef production model is valid for yearling feeder cattle, excluding replacement heifers and bulls, exposed to average daily temperatures greater than 15°C (NRC, 1996). For the purposes of this study, the animal is grown from 350 kg to a 550 kg slaughter weight. The animal is assumed to be a beef breed, not emaciated or obese, have an anabolic implant and the lot condition is assumed to be dry. The beef model (figure 3) is composed of a series of interrelated calculations that are based on the animal's body weight and the air temperature. The net result is an ability to calculate animal production (shrunk weight gain (SWG)) on a daily basis as a function of thermal conditions.

General Circulation Models (GCMs)

The objective of climate modeling is to simulate the processes and predict the effects of imposed changes [forcings] and internal interactions (Henderson-Sellers and McGuffie, 1997) of the climate system. General circulation models are numerical models that estimate the evolution of the atmosphere based on the conservation laws for atmospheric mass, momentum, total energy, and water vapor (Grotch and MacCracken, 1991), requiring recognition of the complex interactions within the ocean-atmosphere system (Washington, 1999; Henderson-Sellers and McGuffie, 1997). A three-dimensional grid system is employed to simulate the characteristics of atmospheric columns and layers.

Global climate models of differing origin make slightly different underlying assumptions about the interactions within the system. These assumptions lead to outputs that are dissimilar among the models. Inconsistencies between the forcing mechanisms applied to a model may also result in different model outputs. This study employs the output of two GCMs, the Canadian Global Coupled Model, Version I (CGCMI), and the United Kingdom Meteorological Office/Hadley Center for Climate Prediction and Research (Hadley) model, for input to the livestock production/response models. These two models yield sundry predictions about future climatic conditions. For example, both models predict increasing temperatures in the future, but the CGCMI model estimates a more rapid increase (USGCRP, 2003). The production response models were run for each climate model with one current and two future climate scenarios: a double CO_2 scenario and a triple CO_2 scenario.

The greenhouse gas forcing employed by the CGCMI corresponds to the levels observed from 1850 to 1985 (baseline), and a level representative of an increase of CO_2 at a rate of 1% per year from the present to the year 2100 (CCCMA, 2000c). The CO_2 level over the period 2040 to 2060 is therefore representative of an approximate doubling of the baseline level, and an approximate tripling for 2080 to 2100 (CCCMA, 2000c). The 24-hr average temperature (°C) at a height of 2m is directly available for the CGCMI scenarios (CCCMA 2000a), and serve as input for the swine and beef cattle models. Additionally, 24-hour average specific humidity (kg/kg), the average of the 00Z and 12Z surface pressure (hPa), and 10-meter wind speed (m/s) provide the data necessary for input to the dairy cattle model. Data are available on an approximate 3.75° grid, approximately 410 km x 222 km in the central United States (CCCMA 2002b).

Instead of actual values for the climate variables, the Hadley model provides monthly coefficients that indicate the degree of change from the baseline climate for each variable. These Hadley change coefficients were used to modify the daily data from the baseline period. Again, the 24-hour average air temperature (°C) at the 2m height, 24-hour average specific humidity, the average of the 00Z and 12Z surface pressure (hPa), and 10-meter wind speed (m/s) provide the climate data necessary for input to the livestock production/response models. The Hadley model data are available for the same 3.75° by 3.75° grid of the CGCMI. This facilitates comparison of the production/response model output.

Greenhouse gas forcing employed by the Hadley model corresponds to an increase of CO_2 at a rate of 1.0% per year. Monthly change coefficients are applied to baseline data to yield daily data representative of the decade when CO_2 reached approximately twice its current level and for the decade when the CO_2 had concentration approximately tripled.

Study Areas

Two study areas are utilized in this study to assess the effects of predicted environmental changes on livestock production in the United States. These are: 1) the four-state, Missouri, Iowa, Nebraska, Kansas (MINK) region, selected for intensive analysis following the rationale of Rosenberg (1993), using six grid points (figure 4); and 2) three transects across the central United States, to provide an intermediate spatial resolution over the Great Plains and South Central regions (15 grid points), (figures 4 and 5). The finest resolution is determined by the resolution of the output data available from the CGCMI global circulation model runs.

In general, the CGCMI predicts an increase in temperature, a slight decrease in precipitation, little change in specific humidity, and a slight reduction in wind speed in the MINK region over the baseline period (CCCMA 2000c). The Hadley model also predicts an increase in summer temperature, but suggests a more pronounced decrease in summer precipitation over the region (NCAR 2000).

For the transects in the Great Plains and South Central regions, an increase in temperature, and a slight decrease in precipitation is predicted by CGCMI over the baseline for the extreme southern and central parts of the region. An increase in specific humidity in the eastern part of the area, and a reduction in wind speed, especially in the western part of the region is also expected (CCCMA 2000c). The Hadley model suggests increased summertime temperatures in the northern parts of the region, but less severe change in temperature in the south. Precipitation change is predicted to be minimal with a slight decrease along the western edge of the study area (NCAR 2000).

Model Procedures

Input of daily GCM output to the previously described livestock production/response models results in daily production values for each species. Weight gain of beef cattle and swine were calculated daily beginning June 1 and the number of days for the animal to grow to the target weight determined for each year. For dairy cattle, daily values of fat corrected milk (FCM) produced (kg) were summed to yield the total production for the season June 1 to October 31 of each year. Annual values are averaged for each of the three climate scenarios (baseline, CO_2 doubling, CO_2 tripling) to produce one value for each scenario at each grid location. A comparison of the averages for CO_2 doubling and for CO_2 tripling with the baseline provides production change scenarios for each climate scenario at each grid location.

Values from each of the beef and swine production/response model runs for each climate scenario were developed as a change in number of days for the animal to reach the target weight. Swine generally reached the final weight early in the study period (July or early August) but beef cattle require more time to reach final weight and in a few cases did not reach the target weight by the end of the study period (October 31 or 153 days). When target weight was not reached, the number of days in the study period was substituted for the number of days to reach the target weight. Dairy production projections were developed in the form of change in kg of fat corrected milk (FCM) produced per cow for the June 1 to October 31 season.

RESULTS

MINK Region

Swine

The CGCMI scenarios project severe losses for the southeastern points of the MINK region and little effect on production in the northwestern parts of the area (table 1). Time to slaughter weight associated with the CGCMI CO_2 doubling scenario ranges from 57 to 87 days. Potential losses under this scenario range from no change to a loss of 24.3% of current production levels. Under the CGCMI CO_2 tripling scenario, time to slaughter weight ranges from 58 to 121 days, a maximum increase of 51 days, or a reduction of 72.9%, over current production levels.

Losses associated with the Hadley scenarios are less severe in the MINK region (table 2). Time to slaughter weight for the CO_2 doubling scenario ranges from 57 to 77 days, no loss to a loss of 9.1% of current production levels. Under the CO_2 tripling scenario, potential losses rise to a maximum of 11 days, 15.7%, of current production levels.

In the MINK region, both models project higher losses at the southeastern points and minimal change in days to slaughter weight in the north and western parts of the region. The CGCMI scenarios project higher levels of loss than the Hadley scenarios.

Beef

In the MINK region the CGCMI CO_2 doubling scenario projects increased time to slaughter weight in all parts of the study area (table 3). These increases range from 0.8% to

8.0% of current production levels. Under the CO_2 tripling scenario, the CGCMI projects more severe production losses in a range from 3.3% to 15.4%.

The Hadley scenarios also predict increased time to slaughter weight at all points in the MINK region, although these projected losses are somewhat smaller than those predicted by the CGCMI scenarios (table 4). Losses under the Hadley CO_2 doubling scenario average 2 to 3 days, 1.6% to 2.4% of current production levels. Increased time to slaughter weight for the Hadley CO_2 tripling scenario range from 3.7% to 4.2% above current production levels.

Results from the CGCMI scenarios suggest a northwest to southeast gradient in the MINK region with the more severe production losses occurring in the southeast. The Hadley scenarios do not display such a north to south gradient, however a moderate east to west gradient is observed.

Dairy

Throughout the MINK region, losses associated with the CGCMI CO_2 doubling scenario range from 53 to 136 kg FCM/cow/season (table 5). Potential losses under this scenario range from 1.2% to 2.7% of current production levels. Under the CGCMI CO_2 tripling scenario, potential losses rise to at least 240 kg FCM/cow/season, a reduction of 5.1% to 6.8% of current production levels. To provide an estimate of potential economic loss to producers under modeled climate, the seasonal averages were multiplied by $.31/kg FCM (University of Nebraska, 1999). This conversion resulted in potential losses of $16 to $42 /cow/season under the CGCMI CO_2 doubling scenario and $74 to $104 /cow/season under the CGCMI CO_2 tripling scenario.

Losses associated with the Hadley scenarios are generally higher than the CGCMI projections for the CO_2 doubling scenario (table 6). These losses range from 109.8 to 163.7 kg

FCM/cow/season or \$34.04 to \$50.57. This is a decrease of as much as 3.1% of baseline production levels. Losses with the Hadley scenario are lower, however, under the CO_2 tripling scenario. Maximum projected production loss is at most 251.7 kg FCM/cow/season with this scenario.

Across Kansas and Missouri, milk production trends for the CGCMI scenarios are inversely related to current temperature. The impact of humidity on VFI coupled with decreased length of the warm season in the northern areas causes the trend to be reversed in Nebraska and Iowa. Milk production decreases with elevated temperature scenarios at all points in the study area. The eastern points are more severely affected by the modeled climates than are western points in the CGCMI scenarios, but little gradient is evident under the Hadley scenarios.

Central United States

Production output data are presented for five points along each of the three transects in the central U.S. shown in figure 5. These points are labeled according to the transect number, T1 (west), T2 (central), T3 (east) and alphabetically from north to south along each transect.

Swine

CGCMI scenarios predict little to no production loss for transect 1 in the CO_2 doubling scenario, and only slight losses at the southern points of the transect for the CO_2 tripling scenario (table 7). The same north to south gradient is observed on all transects. A west to east production gradient is also evident with greater losses in the east. This is consistent with the northwest to southeast gradient observed in the MINK region analysis. Again, the most severe losses are observed in the southeastern parts of the study area. Producers face increases in time to slaughter weight as large as 74% in eastern parts of the region under the CGCMI CO_2 tripling scenario.

The Hadley scenarios do not predict such severe production declines (table 8). A slight northwest to southeast gradient is also evident, but the gradient is much weaker than that predicted by the CGCMI scenarios. This is consistent with the observation that the Hadley model predicts smaller average summer temperature increases than the CGCMI model. Transect 1 shows no losses under the Hadley CO_2 doubling scenario and minimal losses under the CO_2 tripling scenario. Transect 3 displays losses of up to 40.5% under the Hadley CO_2 tripling scenario, more severe at the southern points.

Beef

Under the CGCMI scenarios the pattern of beef production loss appears much the same as swine production losses in the central U.S. A fairly strong northwest to southeast gradient is observed over the three transects (table 9).

The north to south gradient of projected losses for swine production generated by the Hadley scenarios is reversed for beef cattle (table 10). This may be attributed to differences in temperature later in the season. Swine will mature to market weight earlier in the season and will be affected by temperature gradients occurring in June and July. Beef cattle will still be in the growth process later in the warm season and changing temperature gradients projected for August and September will have an effect on beef production levels.

Dairy

CGCMI scenarios project production losses throughout the central U.S., but without a well defined geographical pattern. No strong gradient is evident in the three transects (table 11). Season length may also be a factor in this calculation. The June to October study period may exclude warm days in May that would adversely affect production and include cool days in October that will have little effect. The pattern observed could also be indicative of changes in warm season length under modeled climates and not necessarily a response to changes in temperatures of the warm season.

The Hadley scenarios project higher production declines at northern points on the transects (table 12). Higher levels of baseline milk production in this area may be more severely affected by changes in temperature over the warm season.

IMPLICATIONS

Projected changes in climate induced by increasing CO_2 levels, primarily manifested as increases in air temperature, will markedly reduce milk production levels in the central Great Plains unless counter-acting measures are taken by producers. Swine producers in some areas may experience increases in time to market of up to 74%. Beef producers potentially face up to 16% longer feeding periods and some dairy producers may encounter production losses of more than $100/cow/season.

Quantification of potential impacts of climate change on livestock production allows producers to gain a better understanding of the magnitude of the changes in production levels faced under climate change. Projected economic losses resulting from temperature-induced reductions in production may justify mitigation of these temperature increases through changes in management practices, such as installation of shades or sprinklers in feedlots or evaporative cooling of barns.

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		2x CO_2			3xCO_2		
region	**baseline (days)**	**days**	**change (days)**	**% change**	**days**	**change (days)**	**% change**
NE1	59	57	-2	-3.4	58	-1	-1.7
NE2	59	58	-1	-1.7	63	4	6.8
IA1	59	60	1	1.7	69	10	16.9
KS1	58	57	-1	-1.7	65	7	12.1
KS2	62	68	6	9.7	104	42	67.7
MO1	70	87	17	24.3	121	51	72.9

Table 1. Projected days for swine to grow from 50kg to 110kg beginning June 1 for the baseline and the CGCMI CO_2 doubling and CO_2 tripling scenarios for the MINK region.

		2x CO_2			3xCO_2		
region	**baseline (days)**	**days**	**change (days)**	**% change**	**days**	**change (days)**	**% change**
NE1	59	58	-1	-1.7	58	-1	-1.7
NE2	59	58	-1	-1.7	61	2	3.4
IA1	59	60	1	1.7	66	7	3.4
KS1	58	57	-1	-1.7	61	2	3.4
KS2	62	66	4	6.5	70	8	12.9
MO1	70	77	7	9.1	81	11	15.7

Table 2. Projected days for swine to grow from 50kg to 110kg beginning June 1 for the baseline and the Hadley CO_2 doubling and CO_2 tripling scenarios for the MINK region.

region	baseline (days)	2x CO_2 days	2x CO_2 change (days)	2x CO_2 % change	$3xCO_2$ days	$3xCO_2$ change (days)	$3xCO_2$ % change
NE1	122	123	1	0.8	126	4	3.3
NE2	124	127	3	2.4	134	10	8.1
IA1	126	130	4	3.2	138	12	9.5
KS1	122	124	2	1.6	135	13	10.7
KS2	130	138	8	6.2	150	20	15.4
MO1	138	149	11	8.0	152	14	10.1

Table 3. Projected days for beef cattle to grow from 350kg to 550kg beginning June 1 for the baseline and the CGCMI CO_2 doubling and CO_2 tripling scenarios for the MINK region.

region	baseline (days)	2x CO_2 days	2x CO_2 change (days)	2x CO_2 % change	$3xCO_2$ days	$3xCO_2$ change (days)	$3xCO_2$ % change
NE1	122	125	3	2.5	127	5	4.1
NE2	124	127	3	2.4	129	5	4.0
IA1	126	129	3	2.4	131	5	4.0
KS1	122	124	2	1.6	127	5	4.1
KS2	130	133	3	2.3	135	5	3.7
MO1	138	141	3	2.2	144	6	4.2

Table 4. Projected days for beef cattle to grow from 350kg to 550kg beginning June 1 for the baseline and the Hadley CO_2 doubling and CO_2 tripling scenarios for the MINK region.

		2x CO_2			3xCO_2		
region	**baseline (kg)**	**kg**	**change (kg)**	**change ($)**	**kg**	**change (kg)**	**change ($)**
NE1	5222.8	5114.7	108.1	33.51	4958.6	270.2	83.76
NE2	5204.8	5073.8	131.0	40.61	4896.5	308.3	95.57
IA1	5057.8	4921.1	136.7	42.38	4718.6	339.2	105.15
KS1	4596.9	4543.6	53.3	16.52	4356.0	240.9	74.68
KS2	4673.4	4588.8	84.6	26.23	4400.5	272.9	84.41
MO1	4741.7	4621.2	120.5	37.36	4417.3	324.4	100.56

Table 5. Milk production totals per cow over the June 1 to October 31 season for the baseline and the CGCMI CO_2 doubling and CO_2 tripling scenarios for the MINK region.

		2x CO_2			3xCO_2		
region	**baseline (kg)**	**kg**	**change (kg)**	**change ($)**	**kg**	**change (kg)**	**change ($)**
NE1	5222.8	5061.7	161.1	49.94	4975.4	247.4	76.69
NE2	5204.8	5041.1	163.7	50.57	4953.1	251.7	78.03
IA1	5057.8	4902.3	155.5	48.21	4834.3	223.5	69.29
KS1	4596.9	4487.1	109.8	34.04	4993.8	202.9	62.90
KS2	4673.4	4552.4	121.0	37.51	4456.2	217.2	67.33
MO1	4741.7	4606.3	135.4	41.99	4529.8	211.9	65.69

Table 6. Milk production totals per cow over the June 1 to October 31 season for the baseline and the Hadley CO_2 doubling and CO_2 tripling scenarios for the MINK region.

		2x CO_2			3xCO_2		
region	**baseline (days)**	**days**	**change (days)**	**% change**	**days**	**change (days)**	**% change**
T1a	62	60	-2	-3.2	58	-4	-6.5
T1b	61	59	-2	-3.3	58	-3	-4.9
T1c	60	58	-2	-3.3	57	-3	-5.0
T1d	58	57	-1	-1.7	59	1	1.7
T1e	58	58	0	0	71	13	22.4
T2a	60	58	-2	-3.3	57	-3	-5.0
T2b	59	57	-2	-3.4	58	-1	-1.7
T2c	58	57	-1	-1.7	65	7	12.1
T2d	59	62	3	5.1	86	27	45.8
T2e	61	62	1	1.6	83	22	36.1
T3a	59	58	-1	-1.7	58	-1	-1.7
T3b	59	60	1	1.7	69	10	16.9
T3c	70	87	17	24.3	121	51	72.9
T3d	81	105	24	29.6	141	60	74.1
T3e	79	94	15	19.0	133	54	68.4

Table 7. Projected days for swine to grow from 50kg to 110kg beginning June 1 for the baseline and the CGCMI CO_2 doubling and CO_2 tripling scenarios for the central United States.

		2x CO_2			3xCO_2		
region	**baseline (days)**	**days**	**change (days)**	**% change**	**days**	**change (days)**	**% change**
T1a	62	62	0	0	62	0	0
T1b	61	60	-1	-1.6	62	1	1.6
T1c	60	59	-1	-1.7	60	0	0
T1d	58	57	-1	-1.7	60	2	3.4
T1e	58	58	0	0	63	5	8.6
T2a	60	60	0	0	59	-1	-1.7
T2b	59	58	-1	-1.7	58	-1	-1.7
T2c	58	57	-1	-1.7	61	2	3.4
T2d	59	60	1	1.7	67	8	13.6
T2e	61	62	1	1.6	71	10	16.4
T3a	59	59	0	0	60	1	1.7
T3b	59	60	1	1.7	66	7	11.9
T3c	70	77	7	9.1	81	11	15.7
T3d	81	92	11	13.6	105	24	29.7
T3e	79	90	20	25.3	111	32	40.5

Table 8. Projected days for swine to grow from 50kg to 110kg beginning June 1 for the baseline and the Hadley CO_2 doubling and CO_2 tripling scenarios for the central United States.

		2x CO_2			3xCO_2		
region	**baseline (days)**	**days**	**change (days)**	**% change**	**days**	**change (days)**	**% change**
T1a	125	124	-1	-0.8	122	-3	-2.4
T1b	125	123	-2	-1.6	122	-3	-2.4
T1c	123	122	-1	-0.8	122	-1	-0.8
T1d	121	122	1	0.8	126	5	4.1
T1e	124	125	1	0.8	138	12	9.7
T2a	123	122	-1	-0.8	123	0	0
T2b	122	123	1	0.8	126	4	3.3
T2c	122	124	2	1.6	135	13	10.7
T2d	126	131	5	4.0	146	20	15.9
T2e	128	129	1	0.8	144	16	12.5
T3a	122	123	1	0.8	126	4	3.3
T3b	126	130	4	3.2	138	12	9.5
T3c	138	149	11	8.0	152	14	10.1
T3d	144	153	9	6.3	153	9	6.3
T3e	143	151	8	5.6	153	10	6.9

Table 9. Projected days for beef cattle to grow from 350kg to 550kg beginning June 1 for the baseline and the CGCMI CO_2 doubling and CO_2 tripling scenarios for the central United States.

		2x CO_2			3xCO_2		
region	**baseline (days)**	**days**	**change (days)**	**% change**	**days**	**change (days)**	**% change**
T1a	125	128	3	2.4	130	5	4.0
T1b	125	128	3	2.4	130	5	4.0
T1c	123	125	2	1.6	128	5	4.1
T1d	121	123	2	1.7	125	4	3.3
T1e	124	126	2	1.6	128	4	3.2
T2a	123	126	3	2.4	128	5	4.1
T2b	122	125	3	2.5	127	5	4.1
T2c	122	124	2	1.6	127	5	4.1
T2d	126	127	1	0.8	130	4	3.2
T2e	128	129	1	0.8	132	4	3.1
T3a	122	125	3	2.5	126	4	3.3
T3b	126	129	3	2.4	131	5	4.0
T3c	138	141	3	2.2	144	6	4.3
T3d	144	146	2	1.4	149	5	3.5
T3e	143	145	2	1.4	148	5	3.5

Table 10. Projected days for beef cattle to grow from 350kg to 550kg beginning June 1 for the baseline and the Hadley CO_2 doubling and CO_2 tripling scenarios for the central United States.

region	baseline (kg)	2x CO_2 kg	2x CO_2 change (kg)	2x CO_2 change ($)	3xCO_2 kg	3xCO_2 change (kg)	3xCO_2 change ($)
T1a	4957.5	4831.2	126.3	39.15	4639.9	317.6	98.46
T1b	4906.8	4793.5	113.3	35.12	4560.9	345.9	107.23
T1c	4589.8	4500.9	88.9	27.56	4280.8	309.0	95.79
T1d	4462.3	4352.6	109.7	34.01	4129.5	322.8	130.17
T1e	4459.6	4392.6	66.7	20.68	4216.2	243.4	75.45
T2a	4945.2	4834.4	110.8	34.35	4619.0	326.2	101.12
T2b	5222.8	5114.7	108.1	33.51	4958.6	270.2	83.76
T2c	4596.9	4543.6	53.3	16.52	4356.0	240.9	74.68
T2d	4797.4	4749.3	48.1	14.91	4638.5	158.9	49.26
T2e	4496.6	4399.3	97.3	30.16	4209.6	287.0	88.97
T3a	5000.3	4909.9	9034	28.02	4689.5	310.8	95.35
T3b	5057.8	4921.1	136.7	42.38	4718.6	339.2	105.15
T3c	4741.7	4621.2	120.5	37.36	4417.3	324.4	100.56
T3d	4881.8	4800.8	81.0	25.11	4598.0	283.8	87.98
T3e	4454.4	4348.5	105.9	32.83	4131.9	322.5	99.98

Table 11. Milk production totals per cow over the June 1 to October 31 season for the baseline and the CGCMI CO_2 doubling and CO_2 tripling scenarios for the central United States.

region	baseline (kg)	2x CO_2 kg	2x CO_2 change (kg)	2x CO_2 change ($)	3xCO_2 kg	3xCO_2 change (kg)	3xCO_2 change ($)
T1a	4957.5	4808.0	149.5	43.35	4719.2	238.3	73.87
T1b	4906.8	4757.9	148.9	46.16	4675.4	231.4	71.73
T1c	4589.8	4477.5	112.3	34.81	4394.4	195.4	60.57
T1d	4462.3	4380.6	81.7	25.34	4290.9	171.4	53.13
T1e	4459.6	4380.6	79.0	24.49	4290.5	169.0	52.39
T2a	4945.2	4801.7	143.5	44.49	4724.0	221.2	68.57
T2b	5222.8	5061.7	160.4	49.72	4975.4	246.7	76.48
T2c	4596.9	4487.1	109.8	34.04	4393.8	203.1	62.96
T2d	4797.4	4729.9	67.5	20.93	4610.1	187.3	58.08
T2e	4496.6	4437.5	59.1	18.32	4322.1	174.5	50.10
T3a	5000.3	4846.0	154.3	47.83	4798.3	202.0	62.62
T3b	5057.8	4902.3	155.5	48.21	4834.3	223.5	69.29
T3c	4741.7	4606.3	135.4	41.97	4529.8	211.9	65.69
T3d	4881.8	4774.9	106.9	33.14	4679.7	202.1	62.65
T3e	4454.4	4361.7	92.7	28.74	4272.6	181.7	56.33

Table 12. Milk production totals per cow over the June 1 to October 31 season for the baseline and the Hadley CO_2 doubling and CO_2 tripling scenarios for the central United States.

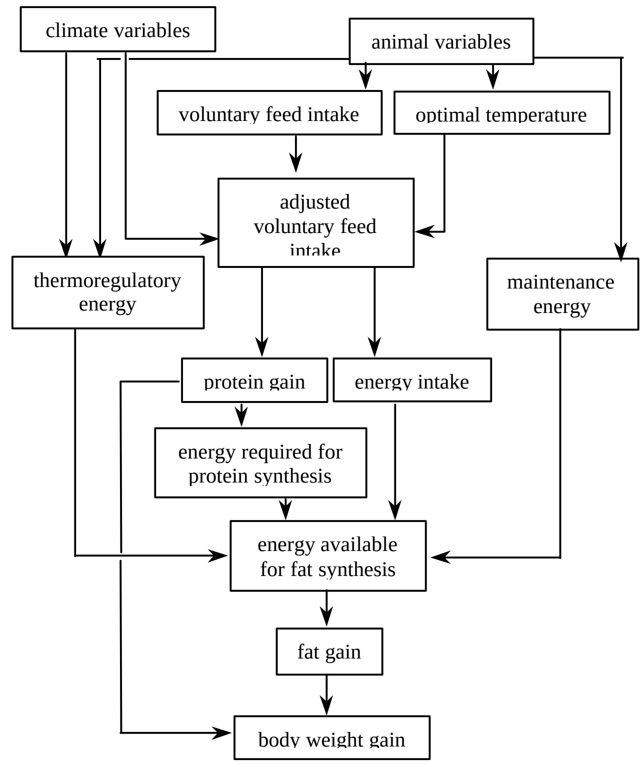

Figure 1. Conceptual model for development of mathematical swine production/response model.

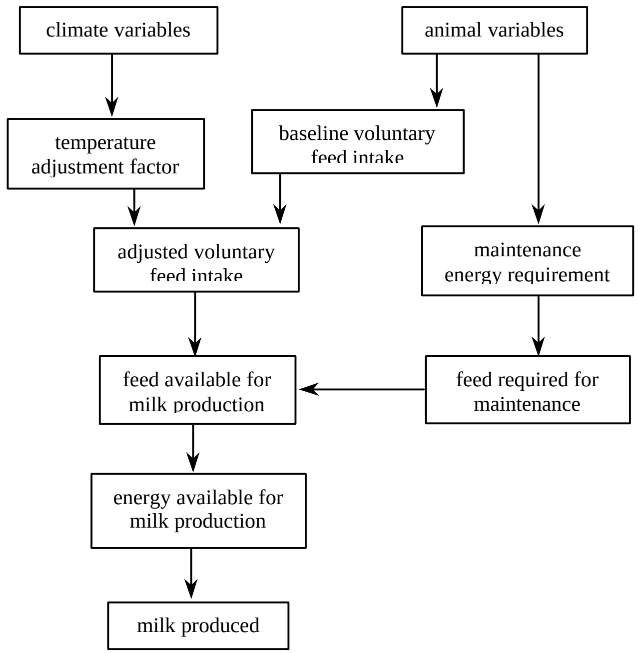

Figure 2. Conceptual model for development of mathematical dairy production/response model.

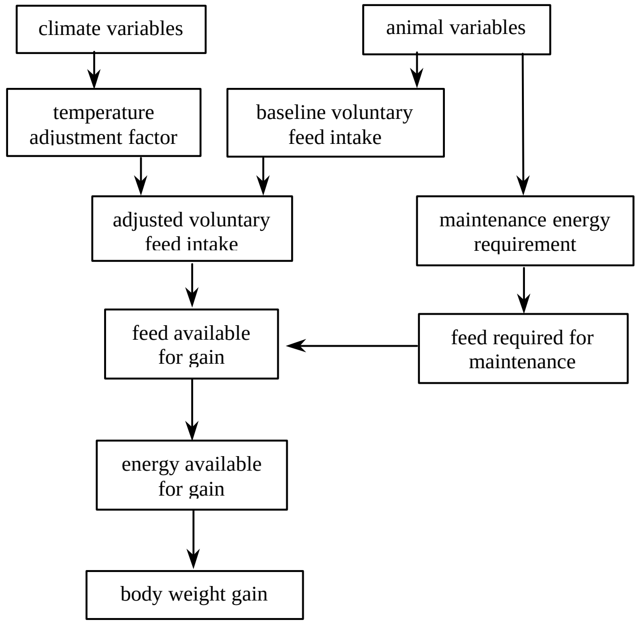

Figure 3. Conceptual model for development of mathematical beef production/response model.

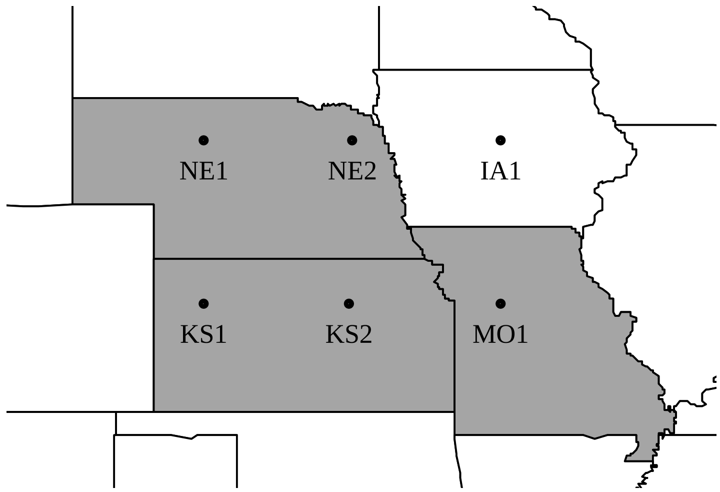

Figure 4. Points analyzed within the Missouri, Iowa, Nebraska, Kansas (MINK) region of the United States.

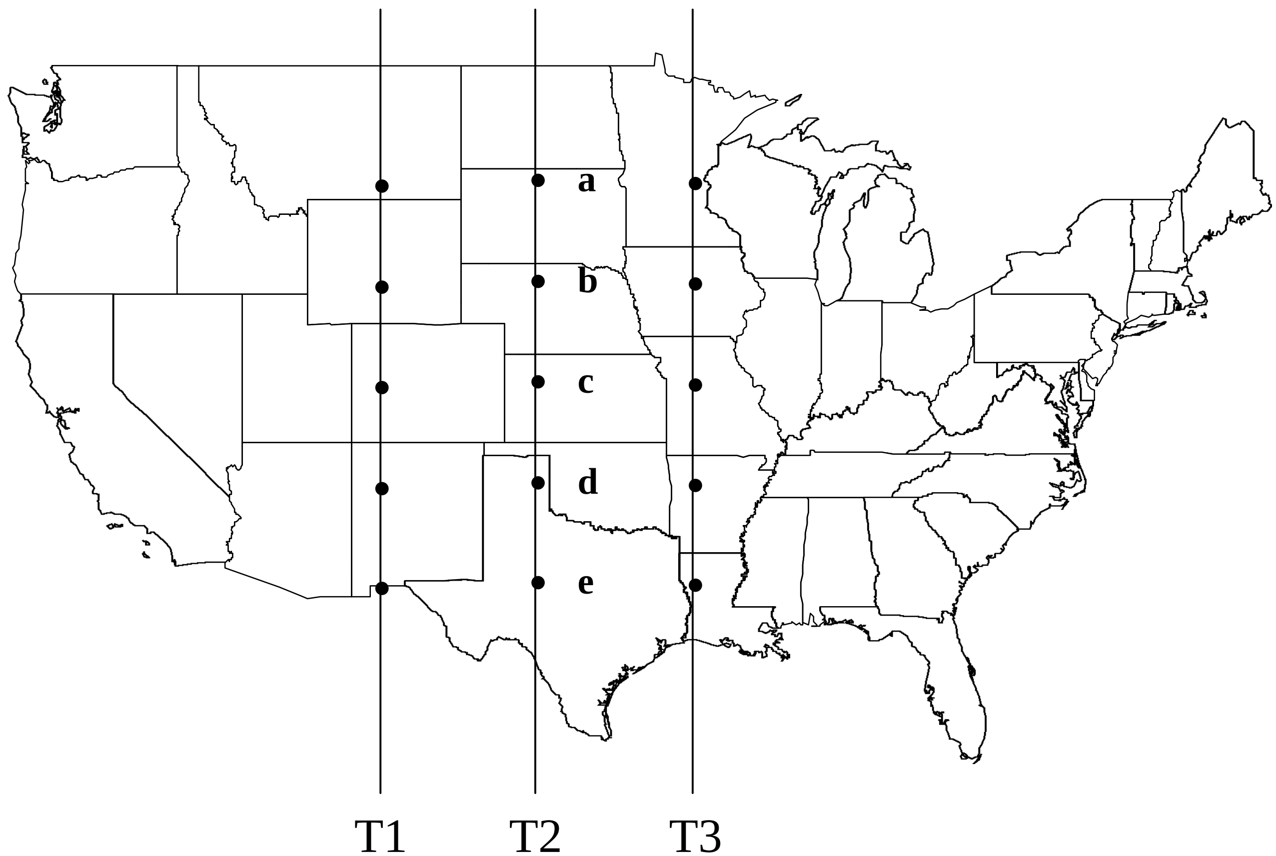

Figure 5. Points analyzed along three transects in the central United States.