THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON ECOSYSTEM PROCESSES AND CATTLE PRODUCTION ON U.S. RANGELANDS

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Abstract. In spite of the uncertainties of potential climate change, a scientific consensus is emerging that increasing concentrations of atmospheric CO_2 could alter global temperatures and precipitation patterns. Changes in global climate as predicted by General Circulation Models (GCM) could therefore, have profound implications for global agriculture. The objective of this study was to assess the impacts of potential climate change on livestock and grassland production in the major producing regions of the United States. Simulation sites were selected for the study on the basis of the region's economic dependence on rangeland livestock production. Five thirty-year simulations were conducted on each site using the Simulation of Production and Utilization of Rangelands model and Colorado Beef Cattle Production Model. Climate change files were obtained by combining historic weather data from each site with predicted output from three GCM's. Results from nominal runs were compared with the three climate change scenarios and a doubled CO_2 run. The magnitude and direction of ecosystem response to climate change varied among the GCM's and by geographic region. Simulations demonstrated that changes in temperature and precipitation patterns caused an increase in above-ground net primary production for most sites. Increased decomposition rates were recorded for northern regions. Similarly, animal production in northern regions increased, implying an increase in economic survivability. However, because decreases in animal production indicators were recorded for the southern regions, economic survivability in southern regions is less certain.

Introduction

The contribution of anthropogenic 'greenhouse' gases, in particular carbon dioxide (CO_2), to global climate change has been the focus of many debates and numerous scientific papers (Laurmann, 1986; Dickinson, 1989; Idso, 1989; Solow and Broadus, 1989; Baliunas, 1990; Jastrow, 1990; Lindzen, 1990; Nierenberg, 1990; Roberts, 1990; Stuiver, 1990; Mohnen *et al.*, 1991). Despite the debate over the effects of CO_2 on the Earth's climate, the fact that atmospheric concentrations are

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rising is indisputable (Keeling *et al.*, 1984; Keeling, 1986; Boden *et al.*, 1990). Over the last century, concentrations of CO_2 have increased from approximately 280 ppm to current levels of 350 ppm and are expected to continue to increase at a rate of 1.8 ppm per year (Rosenberg, 1988; Dickinson, 1989; Watson *et al.*, 1990). Increases in atmospheric CO_2 concentrations over the past 100 y may have contributed to an estimated global warming of 0.5 °C (Wigley *et al.*, 1985). In spite of uncertainties concerning climate change, a scientific consensus is emerging that increasing concentrations of atmospheric CO_2 could alter global temperatures (Rosenberg, 1988; Crosson, 1989; Harvey, 1989; Rosenzweig, 1989; Schneider, 1989; Woodwell, 1989). Predictions from General Circulation Models (GCM's) indicate that with a doubling of atmospheric carbon dioxide, the average global temperature may rise from 1.5 to 5.5 °C (Hansen *et al.*, 1983; Manabe and Wetherald, 1987; Rosenzweig, 1989; Mitchell *et al.*, 1990).

Changes in global climate, as predicted by the GCM's, could have profound implications for world agricultural production. Many researchers have used output from GCM's and analog climate scenarios in an attempt to predict the sensitivity of cultivated agriculture to a CO_2 enhanced warm climate (Bergthorsson, 1985; Oram, 1985; Parry and Carter, 1985; Rosenzweig, 1985; Arthur and Abizadeh, 1988; Rosenberg, 1988; Adams, 1989; Smith and Tirpak, 1989; Adams *et al.*, 1990). However, relatively little research has been conducted to examine the response of rangeland ecosystems to 'greenhouse' warming. Schimel *et al.* (1990) and Hunt *et al.* (1991) used the CENTURY model and Grassland Ecosystem Model (GEM) respectively to examine the effects of climate change on grasslands in the Great Plains of the United States. In neither study were the effects of climate change on livestock production examined.

The objective of this study was to assess the impacts of potential climate change on rangeland primary production and beef cattle in the major producing regions of the United States. In this study a rangeland was defined as a grassland that is primarily used for the grazing of domestic beef cattle.

Methods

Model Description

SPUR (Simulation of Production and Utilization of Rangelands) is a general grassland ecosystem simulation model (Wight and Skiles, 1987). The model is driven by daily inputs of precipitation, maximum and minimum temperatures, solar radiation, and daily wind run. These variables are derived either from existing weather records or from use of a stochastic weather generator. The soils/hydrology component calculates upland surface run-off volumes, peakflow, snowmelt, upland sediment yield, and channel streamflow and sediment yield. Soil-water tensions, used to control various aspects of plant growth, are generated using a soil-water balance equation. Surface run-off is estimated by the Soil Conservation Service curve number procedure and soil loss is computed by the modified universal soil loss equation. The snowmelt routine employs an empirical relationship between air temperature and energy flux of the snowpack.

In the plant component, carbon and nitrogen are cycled through several compartments including standing green, standing dead, live roots, dead roots, seeds, litter, and soil organic matter. Soil inorganic nitrogen dynamics are also simulated. The model simulates competition between plant species and the impact of grazing on vegetation. The plant growth subroutine of the model simulates the direct effects of increased ambient concentrations of CO_2 on net photosynthetic rate. Required initial conditions include the initial biomass content for each compartment and parameters that characterize the species to be simulated (Hanson *et al.*, 1988).

The SPUR model has been subjected to many validation tests. The hydrology components of the model have been validated by Cooley *et al.* (1983), Renard *et al.* (1983), and Springer *et al.* (1984). Predictions of plant growth have been successfully validated by Skiles *et al.* (1983) and Hanson *et al.* (1988).

For this study a new animal production model was incorporated into the SPUR model. CBCPM (Colorado Beef Cattle Production Model), is a herd-wide, life cycle simulation model and operates at the level of the individual animal. The Colorado model was designed to be a flexible research tool. Through the use of both input files and rule writing, CBCPM allows for (1) a variable time step of 1 to 30 days; (2) a variable herd size; (3) the importation of replacement heifers and stocker cattle; (4) the ability to simulate the effects of different cross-breeding systems; and (5) the evaluation of the effects of animal selection over time.

The biological routines of CBCPM simulate animal growth, fertility, pregnancy, calving, death, and demand for nutrients. Currently, fourteen genetic traits related to growth, milk, fertility, body composition, and survival can be studied.

Intake of grazed forage is calculated by FORAGE, a deterministic model that interfaces CBCPM and SPUR (Baker *et al.*, 1992). The model is driven by weight from the animal growth curve, the animal's demand for grazed forage and the quantity and quality of forage available for each time step of the simulation. FORAGE determines the intake of grazed forage by simulating the rate of intake and grazing time of each animal in the time step.

CBCPM is a new model, however, most of the equations describing physiological and biological processes have been used and validated in previous models (Notter, 1977; Sanders and Cartwright, 1979; Bourdon, 1983; Field, 1987). In a preliminary validation, model output was consistent with observed data for intake, average daily gain, milk production, and calf weaning weight (Baker, 1991).

Site Selection

Sites chosen for the simulations were selected based on a county's economic dependence upon rangeland beef cattle production. Every county in the continental United States was evaluated. A Range Dependency Index (*RDI*) was developed to determine the economic importance of livestock grazing in a county. The *RDI* is the percent of a county's income derived from unfed beef cattle sales, e.g. cull cows, cull bulls, weaned calves and yearling animals that have not been grain-fed. The RDI is calculated as:

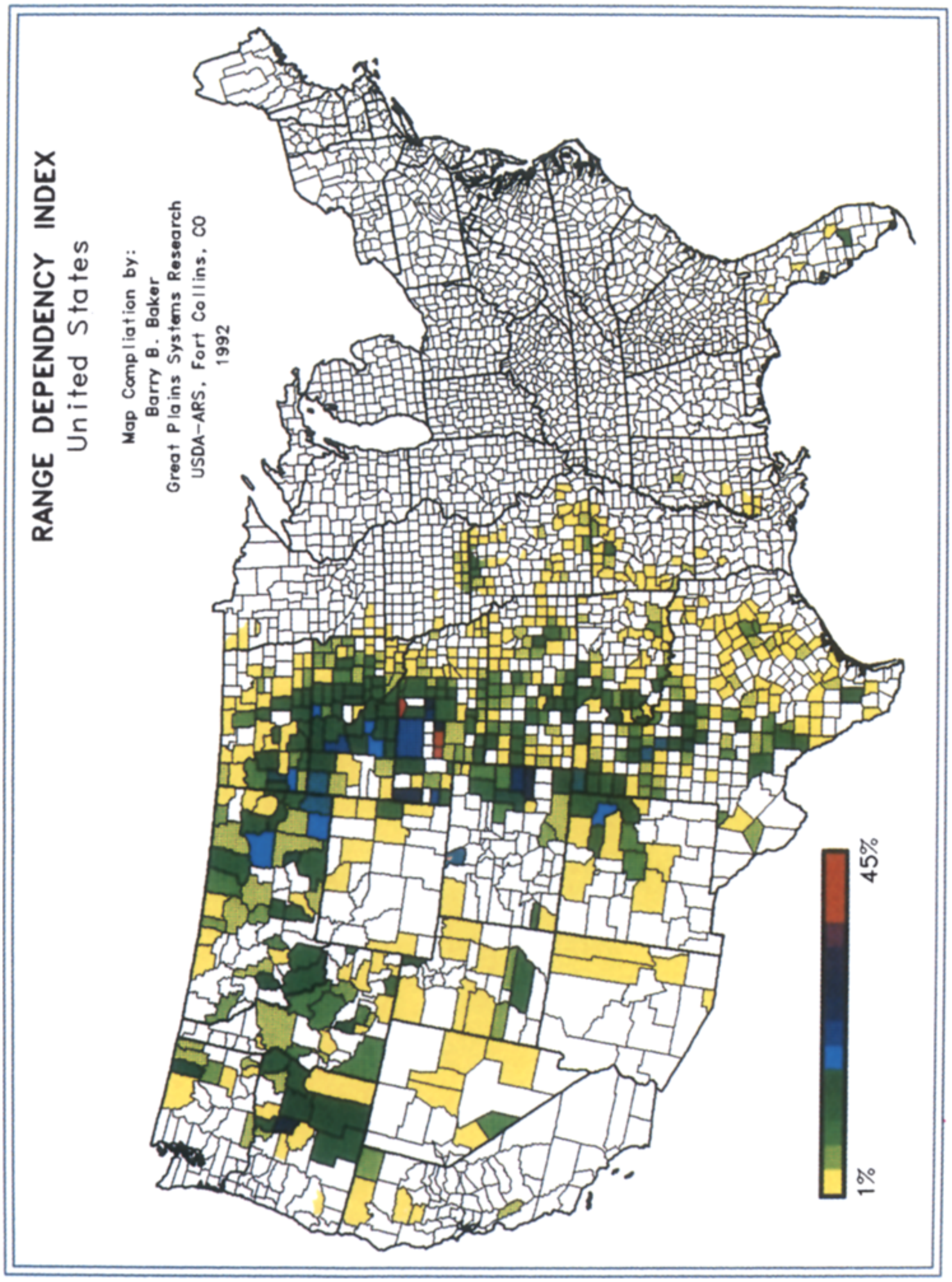
$$RDI = \frac{Value\ of\ range\ prod.}{Total\ farm\ sales} \times \frac{Farm\ income}{Total\ income} \times 100$$

Data needed to calculate the *RDI* were obtained from the 1987 Local Area Personal Income (U.S. Dept. Commerce Bur. of Econ. Anal., 1987) and the 1987 Census of Agriculture (U.S. Dept. Commerce Bur. of Census, 1987) data bases.

The *RDI* was calculated by using the Geographical Resources Analysis Support System (GRASS), a Geographic Information System (GIS) developed by the U.S. Army Corps of Engineers (USA-CERL, 1988). Data needed for the calculations were indexed by a county FIPS (Federal Information Processing System) code (Figure 1). Values ranged from 1% (yellow) to 46% (red). Areas of white in all maps indicated that no data were available for that county or that values were less than 1%.

There were far too many counties at this point to use every county as a separate simulation site. Many of the sites could be lumped because general characteristics of the sites are much the same. To accomplish this grouping, data from the 1982 SCS National Resource Inventory (NRI) (USDA-SCS and ISU Statistics Laboratory, 1982) was sorted by Major Land Resource Area (MLRA) for soils that were classified as rangeland soils, livestock grazing as a primary use, and a range condition equal to good. MLRA's are defined as geographic areas with relatively homogenous patterns of soil, climate, water resources, land use, and type of farming. Each of the 109 polygons from Figure 2a represents an MLRA. A subsample was extracted from Figure 2a to include only those MLRA's that had at least 1000 Primary Sample Units (PSU). A PSU is defined as a tract of land, typically square or rectangular, approximately 40, 100, 160, or 640 acres and is the sample unit at the first stage of sampling in a multisample plan (USDA-SCS and ISU Statistics Laboratory, 1982). The resultant subsample contained 46 MLRA's. (Figure 2b). Simulation sites were chosen as centroid locations within a MLRA. Five MLRA's (35, 42, 43, 67, and 80A) were considered too long to use a centroid position for a representative site, therefore, the MLRA was divided in half and a centroid location was chosen in each half. The actual number of simulation sites were 51 (Table I). Two MLRA's in Texas and Florida could not be simulated because of inadequate data or model performance in subtropical regions, MLRA 86 and 115 respectively.

Fig. 1. Range Dependency Index (*RDI*) for the United States. ▶


RANGE DEPENDENCY INDEX
United States
Map Compliation by:
Barry B. Baker
Great Plains Systems Research
USDA-ARS, Fort Collins, CO
1992
1%
45%

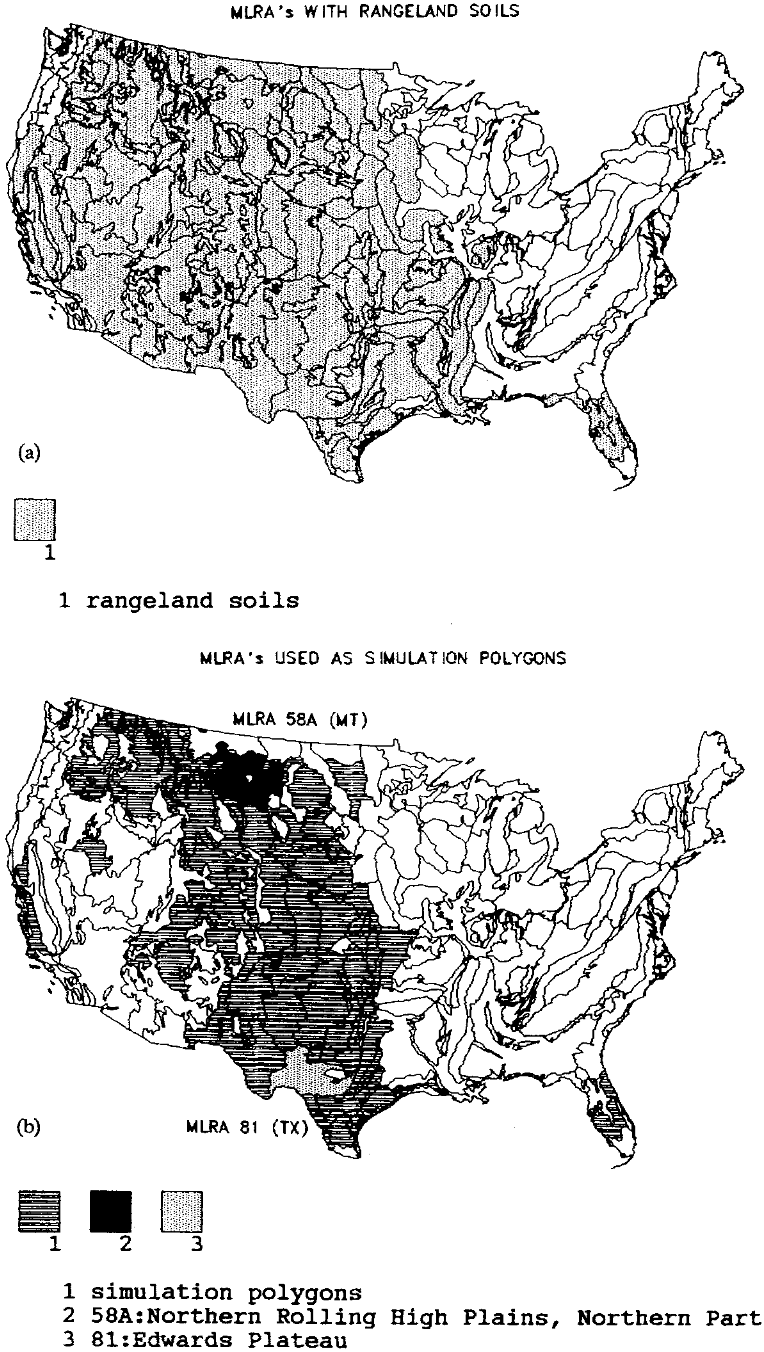


Fig. 2. (a) MLRA's that are classified as having rangeland soils; (b) MLRA's with simulation sites and MLRA's 58a and 81 that were used as representative simulation sites.

TABLE I: State and Major Land Resource Areas (MLRA) number and names used for simulation sites

State	MLRA	Name	State	MLRA	Name
AZ	35	: Colorado and Green River Plateaus	NM	70	: Pecos-Canadian Plains and Valleys
			NV	24	: Humbolt Area
CA	15	: Central California Coast Range	OK	80A	: Central Rolling Red Prairies
CO	34	: Central Desertic Basins, Mountains & Plateau	OK	84A	: Cross Timbers
			OR	10:	Upper Snake River Lava Plains and Hills
CO	48A	: Southern Rocky Mountains			
CO	67	: Central High Plains	SD	60A	: Pierre Shale Plains and Badlands
CO	69	: Upper Arkansas Valley Rolling Plains	SD	63A	: Northern Rolling Pierre Shale Plains
ID	43	: Northern Rocky Mountains	SD	63B	: Southern Rolling Pierre Shale Plains
KS	72	: Central High Tableland			
KS	73	: Rolling Plains and Break	TX	42	: Southern Desertic Basins, Plains & Mountains
KS	74	: Central Kansas Sandstone Hills			
KS	75	: Central Loess Plains	TX	77	: Southern HIgh Plains
KS	76	: Bluestem Hills	TX	78	: Central Rolling Red Plains
KS	112	: Cherokee Prairies	TX	80A	: Central Rolling Red Prairies
MT	44	: Northern Rocky Mountain Valleys	TX	80B	: Texas North-Central Prairies
MT	46	: Norhern Rocky Mountain Foothills	TX	81	: Edwards Plateau
			TX	83A	: Northern Rio Grande Plain
MT	58A	: Norhern Rolling High Plains, Northern Part	TX	83B	: Western Rio Grande Plain
			TX	83C	: Central Rio Grande Plain
ND	54	: Rolling Soft Shale Plain	TX	84B	: West Cross Timbers
ND	55B	: Central Black Glaciated Plains	TX	85	: Grand Prairie
NE	64	: Mixed Sandy and Silty Table	TX	87	: Texas Claypan Area
NE	65	: Nebraska Sand Hills	TX	150A	: Gulf Coast Prairies
NE	66	: Dakota-Nebraska Eroded Tableland	UT	35	: Colorado and Green River Plateaus
NE	71	: Central Nebraska Loess Hill	WA	8	: Columbia Plateau
NE	75	: Central Loess Plains	WY	43	: Northern Rocky Mountains
NM	42	: Southern Desertic Basins, Plains & Mountains	WY	58B	: Norhtern Rolling High Plains, Southern Part
NM	48A	: Southern Rocky Mountains	WY	67	: Central High Plains

Model Parameterization

To parameterize the hydrological component of the SPUR model, hydrological properties of the soils to be simulated were calculated (Springer and Lane, 1987). Two data bases were used for this process. Representative rangeland soils for the MLRA's chosen were identified from the 1992 NRI data base. Soils that had the largest expansion factor for each MLRA were chosen to be the representative soil for the MLRA. The expansion factor is defined as the number of acres the sample point represents. The expansion number takes into account the sampling procedure and the state's census acreage (USDA-SCS and ISU Statistics Laboratory, 1984).

Once a representative soil was identified from the 1982 NRI, the distributions for slope, slope length, USLE K, USLE C, and USLE P factors were determined and the mode value was selected to represent the soil. Secondly, the SCS-Soils-5 data base was used to calculate the average hydrological properties for each soil.

Historical weather data were collected from the EarthInfo Inc. Climate Data from the National Climate Data Center. The data were used to determine the nominal weather scenario for each site. Sites for climate data within a MLRA were selected based on the completeness of the weather record from 1951 through 1980, an *RDI* value of greater than 1% and a central location within the MLRA wherever possible. Daily records for maximum and minimum temperature (°C) and precipitation (mm) were recorded.

Data for daily wind run (km day^{-1}) and daily solar radiation (langleys) were unavailable in the data base and had to be simulated. A weather generation model (CLIMGN) was used to calculate both solar radiation and wind run. CLIMGN is based on a model described by Richardson (1981). A complete description of CLIMGN can be found in the SPUR user guide (Richardson *et al.*, 1987).

To obtain initial values for the phytomass state variables, SPUR was exercised for 30 y using the standard input parameters for warm and cool season grasses, warm and cool season forbs, and shrubs (Hanson and Skiles, 1987). Site specific hydrology input files and the historical climate data files were used for each site. Ending values for the phytomass state variables were used as the initial conditions for the nominal and climate change scenarios for each of the simulation sites.

The methodology for implementing climate change scenarios in conjunction with simulation modelling followed the United States Environmental Protection Agency's (EPA) procedure as described by Smith and Tirpak (1989). General Circulation Model (GCM) output from the Goddard Institute for Space Studies (GISS) (Hansen *et al.*, 1983), Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald, 1987), and the United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell, 1987) models were provided by the National Center for Atmospheric Research (NCAR). Ratios of mean monthly temperature, precipitation and solar radiation from doubled carbon dioxide equilibrium simulations were applied to the historical weather data.

Five 30 y simulations per site were conducted. The historical climate data files from each of the sites were used for the 'NOMINAL' scenario. The second scenario evaluated was the '$2 \times CO_2$' simulation. In this scenario, the nominal climate data were used for each site and the atmospheric concentration of carbon dioxide was raised to 550 ppm. For the three GCM scenarios, the nearest grid point to a simulation site was selected and the historical daily weather data were adjusted for a doubled atmospheric concentration of CO_2 by the recommended adjustment statistic for average temperature, precipitation, and solar radiation.

Indicator Variables

Indicator variables are model derived state or intermediate variables that are used to test the hypotheses under examination. Soil organic matter (SOM) was used to monitor the status of below-ground nutrient sources. Peak standing crop (PSC) was used to determine the effect of climate change on plant production. The carbon to nitrogen ratio (C:N) of the above-ground biomass was used to indicate changes in plant tissue quality.

Diet quality, intake of grazed forage, and a forage to supplement ratio were used to evaluate the effect of climate change on feed intake. Calf weaning weights were used to monitor the climatic effects on calf performance.

The model does simulate warm and cool season grasses and competition for resources between functional groups, however, the model was not constructed to be a successional model. Consequently, shifts in community structure with a change in climate were not investigated.

Representative Sites

Two sites were chosen to evaluate the potential effects of climatic change on selected indicator variables during the year. The sites chosen were in MLRA's 58A (MT) and 81 (TX). These sites were chosen based on geographic separation. SAS version 6.0 (SAS, 1990) was used to calculate monthly means for each simulation scenario. Change from nominal predictions was represented graphically for each scenario.

Summary of Model Runs

For each site within the chosen MLRA, the model was run for 30 y of actual weather data, under five different climate patterns. Averages were used for soil and hydrological data within each MLRA. A constant management and animal type was used for all model runs. Environmental factors such as diseases and pests were not considered.

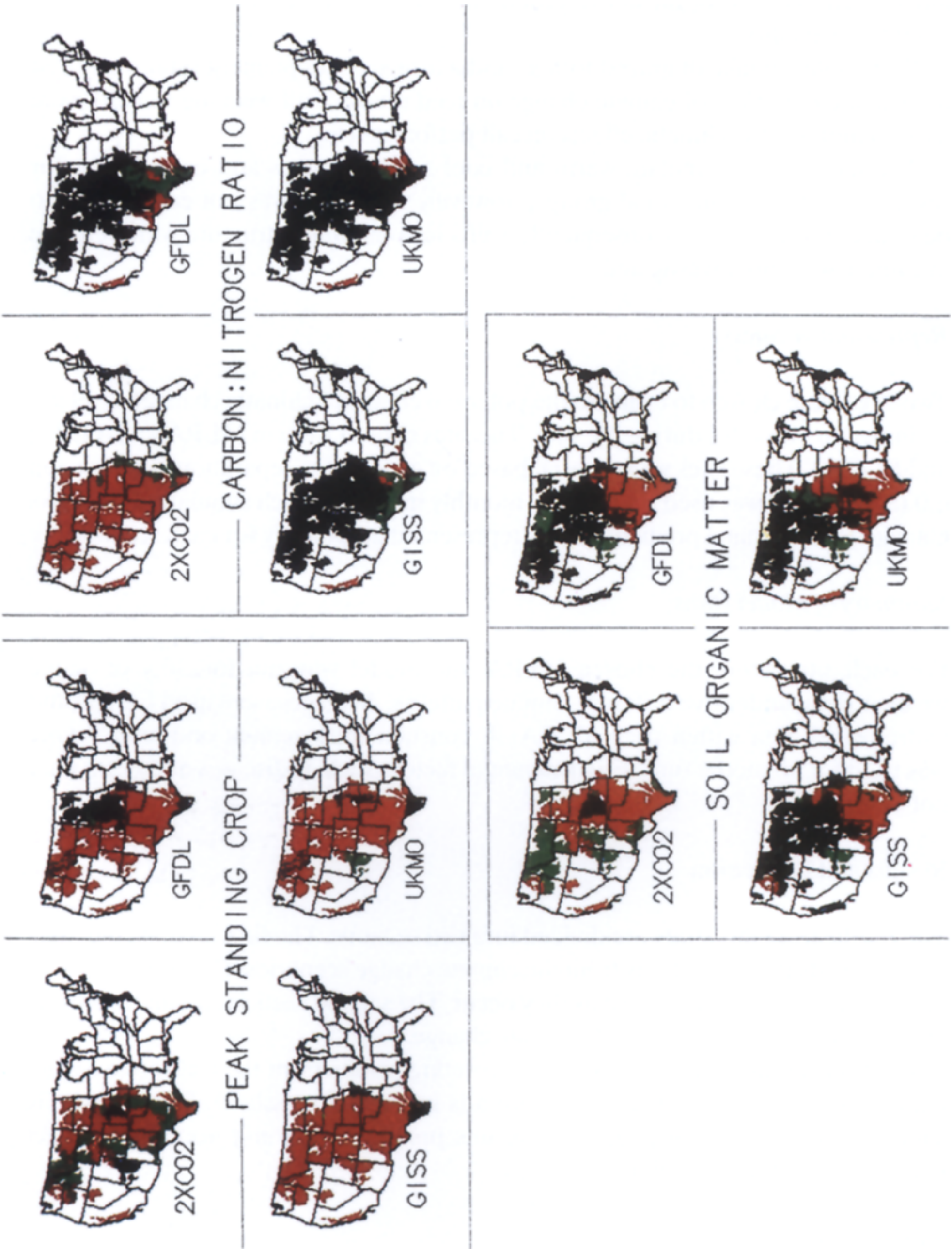
Results and Discussion

The results from this study are divided into two sections. The first section compares and contrasts the predictions from the climate change scenarios. Differences in scenario predictions are discussed as they occur. The second section summarizes overall regional responses to possible climate change.

Caution should be applied when interpreting results from the California rangelands. The region simulated in California is an annual grassland. Because SPUR simulates only perennial plants, the results presented may not accurately reflect plant response for this region.

Climate Change Scenarios

In general climate change had a positive effect on peak standing crop (Figure 3). The map shows the change, either an increase (red), decrease (black), or no change


CARBON:NITROGEN RATIO
GFDL
UKMO
2XCO2
GISS
PEAK STANDING CROP
GFDL
UKMO
2XCO2
GISS
SOIL ORGANIC MATTER
GFDL
UKMO
2XCO2
GISS

(purple), in all simulation sites for the selected indicator variables when the climatic change scenario was compared to the nominal run. The GISS and the UKMO scenarios showed an increase in peak standing crop for most of the sites simulated (Figure 3).

The doubled CO_2 scenario produced the most variable results (Figure 3). No change in PSC was shown for western Texas, southern New Mexico and some areas in the eastern part of the Great Plains. A decrease in PSC was demonstrated in two areas.

A decrease in peak standing crop was simulated by the GFDL scenario for a large portion of the Northern Great Plains (North and South Dakota, Nebraska, and Kansas), the southern tip of Texas and in the northern Rocky Mountain Valleys (Figure 3). Changes in temperature and precipitation patterns predicted by GFDL resulted in higher annual mean PET for these regions. Consequently, less soil moisture was available for plant growth. Generally an increase in PSC was found for the rest of the sites.

Increased plant production simulated by the GCM scenarios had a large effect on the plant-soil system. Increased above-ground biomass resulted in increased input to the soil organic pool. Because of modified temperature and precipitation patterns in the Northern Great Plains, the Intermountain regions, California, and the Northwest, decomposition rates increased. Consequently, soil organic matter decreased and available nitrogen for plant uptake increased. The GFDL, GISS, and UKMO scenarios predicted approximately a 10% decrease in soil organic matter for most of the simulation sites in the northern latitudes (Figure 3). As a result the C:N ratio declined for these regions (Figure 3). In a simulation study, Schimel *et al.* (1990) reported a similar trend in decomposition rates and nitrogen availability for rangelands in the Great Plains.

Soil organic matter was predicted to increase approximately 15% for the Southern Great Plains states (Figure 3). The accumulation of SOM can be attributed to a complex interaction among the environment, the forage, and the grazing activity of the cattle. Increased plant production was caused by an increase in the length of the growing season and generally improved environmental conditions for plant growth. These factors combined with decreased forage intake resulted in a build-up of standing dead plant material and litter. The rate of decomposition decreased because of changes in water distribution. Ultimately, the accumulation of soil organic matter tied up soil nitrogen which resulted in an increase in the C:N ratio for the above-ground biomass (Figure 3).

Moisture and temperature shifts not only increased peak standing crop but also resulted in a change in the growing season. Hunt *et al.* (1991) also found that

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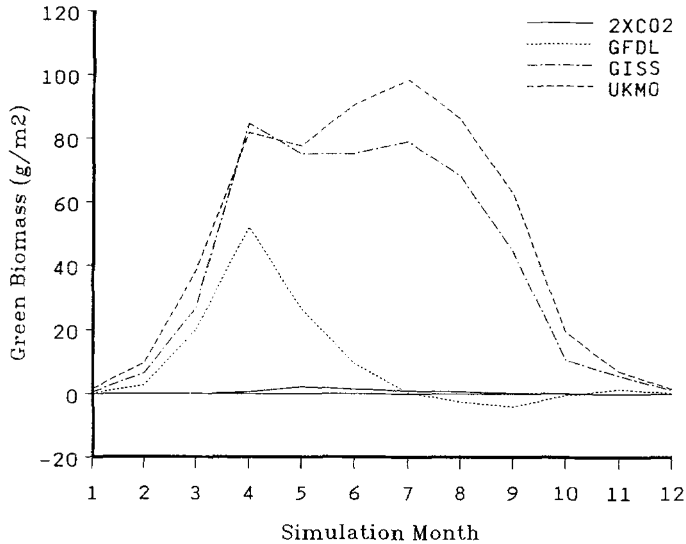
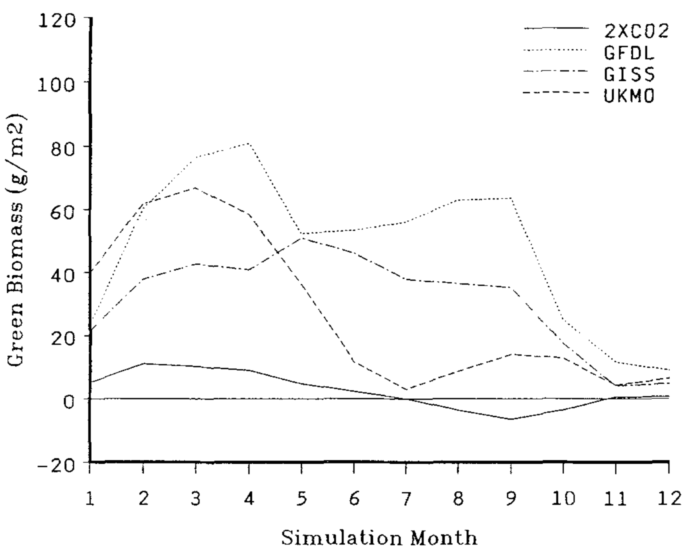
Fig. 3. Regional changes from the NOMINAL simulation scenario for peak standing crop, soil organic matter, and carbon:nitrogen ratio in above-ground biomass for the $2 \times CO_2$, GFDL, GISS, and UKMO simulation scenarios. Red indicates an increase, green is no change from NOMIMAL and black indicates a decrease.

changes in temperature increased the length of the growing season. Evaluation of the two representative sites, MLRA's 58A (MT) and 81 (TX), revealed an increase for springtime primary production for all GCM scenarios (Figure 4a and 4b).

Increased forage intake was predicted for the northern latitudes for all three scenarios (Figure 5). Forage consumption increased as a result of an increase in diet



(a)



(b)

Fig. 4. (a) Changes in monthly means of 30 y simulation runs using four climate change scenarios for green biomass (kg/ha). Representative site in MLRA 58A (MT). (b) Changes in monthly means of 30 y simulation runs using four climate change scenarios for green biomass (kg/ha). Representative site in MLRA 81 (TX).

digestibility (Figure 5), an earlier break in plant dormancy and increased forage production throughout the growing season. Because of the earlier spring growth, less supplemental feed was needed, resulting in a greater forage to supplement ratio (F:S) (Figure 5). However, the coefficient of variation for the F:S was very large for many of the simulation sites. The large variation in estimated F:S ratios indicated a substantial amount of yearly variation in the timing of the spring 'green-up'. Calf weaning weight was predicted to increase 20% for northern latitudes (Figure 5).

Results from the northern representative site, MLRA 58A (MT), showed that all GCM scenarios predicted greater spring-time forage intake and consequently, a decrease in the amount of spring-time supplement (Figure 6a and 6b). Summertime intake was lower than nominal because of increased temperatures and lower forage quality (Figure 6c).

Predictions for animal production in the South and California were less positive. Forage consumption declined because of higher summer temperatures and decreased forage quality (Figure 5). Calf weaning weights were 6% lower than nominal because of higher temperatures, reduced forage quality, and lower milk consumption (Figure 5). The forage to supplement ratio decreased for the Southern Great Plains (Figure 5).

Reductions in forage intake and forage digestibility were predicted by all GCM scenario simulations for the southern representative site MLRA 81 (TX) (Figure 7a and 7b). Because forage intake was reduced, more supplement was needed (Figure 7c).

Overall Regional Response

Both the magnitude and the direction of ecosystem responses to climate change varied at times among the GCM scenarios and by geographical region. The purpose of this study was to examine the regional sensitivity of rangeland ecosystems to possible climatic changes. Therefore, the ecosystem response was summarized as an aggregate response for the three scenarios (Table II). An increase or decrease in the response variables was based on the percentage change when compared to the nominal simulation. For ease of discussion the simulated areas were divided into five regions, the Northern Great Plains, the Southern Great Plains, the Intermountain region, the Northwest, and California. Equal weight analysis showed that three of the five regions defined had a positive response to climate change as predicted by the three GCM scenarios (Table II). Generally, both plant and animal production increased for the northern latitudes. This was consistent with simulation studies of the effects of climate change on agricultural crops (Smith and Tirpak, 1989; Adams *et al.*, 1990; Singh and Stewart, 1991).

Although simulated plant and animal production was greater for the northern region, the ecosystem may not be able to sustain cattle production at the levels simulated in this study. Because of the increased decomposition rates in this region,


DIGESTIBILITY
2XCO2
GFDL
GISS
UKMO
WEANING WEIGHT
2XCO2
GFDL
GISS
UKMO
FORAGE INTAKE
2XCO2
GFDL
GISS
UKMO
FORAGE : SUPPLEMENT RATIO
2XCO2
GFDL
GISS
UKMO

TABLE II: Equal weight analysis of the regional aggregate response from the GCM scenarios for selected indicator variables (Beneficial = + 1, Detrimental = – 1, and No Change = 0)

Variable	Region				
	Northern Great Plains	Southern Great Plains	Inter-Mountain	North-West	California
Plant Variables					
Peak Standing Crop	Increase[1]	Increase	Increase	Increase	Increase
C:N	Decrease[2]	Increase[1]	Decrease	Decrease	Increase
Soil Organic Matter	Decrease	Increase	Decrease	Decrease	Decrease
Animal Variables					
Intake	Increase	Decrease	Increase	Increase	No Change
Digestibility	Increase	Decrease	Increase	Increase	Decrease
F:S	Increase	Decrease	Increase	Increase	Increase
Weaning Weight	Increase	Decrease	Increase	Increase	Decrease
Plant Response	+ 1	+ 1	+ 1	+ 1	– 1
Animal Response	+ 4	– 4	+ 4	+ 4	– 1
Total Response	+ 5	– 3	+ 5	+ 5	– 2

[1] Two out of three GCM's predicted an increase.
[2] A decrease in the C:N ratio is a beneficial response.

soil organic matter was leaving the system faster than it could be replaced. Eventually the deficit of organic matter could destablize the system if stocking rates remain unchanged.

For the Southern Great Plains a slight increase in plant productivity was predicted. Soil organic matter increased for this region, which would imply a more stable environment for plant production. Animal performance, however, was greatly reduced which resulted in a large predicted decrease for the total system response. The genotype of the animals simulated in this study was parameterized for *Bos taurus* cattle. If the genetic parameters had been set to reflect the genotype of a more heat tolerant animal, such as *Bos indicus* cattle, animal performance may not have declined as much in the southern simulation regions.

Conclusions

These model results demonstrate the sensitivity of present-day rangeland livestock production to specific climatic perturbations. To assume that agricultural practices remain unchanged during the simulation period is unrealistic. In fact, agricultura-

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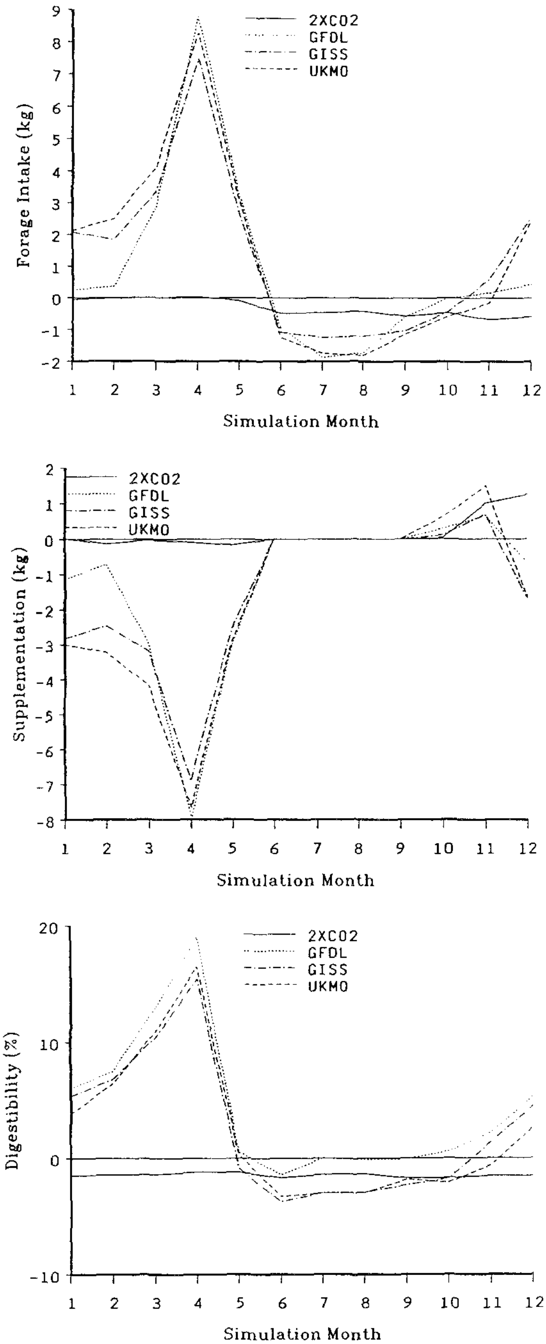
Fig. 5. Regional changes from the NOMINAL simulation scenario for forage intake, forage digestibility, forage:supplement ratio, and calf weaning weight for the 2 × CO_2, GFDL, GISS, and UKMO simulation scenarios. Red indicates an increase, green is no change from NOMINAL and black indicates a decrease.



(a)

(b)

(c)

Fig. 6. (a) Changes in monthly means of 30 y simulation runs using four climate change scenarios for forage intake (kg). Representative site in MLRA 58a (MT). (b) Changes in monthly means of 30 y simulation runs using four climate change scenarios for supplementation (kg). Representative site in MLRA 58a (MT). (c) Changes in monthly means of 30 y simulation runs using four climate change scenarios for digestibility (%). Representative site in MLRA 58a (MT).

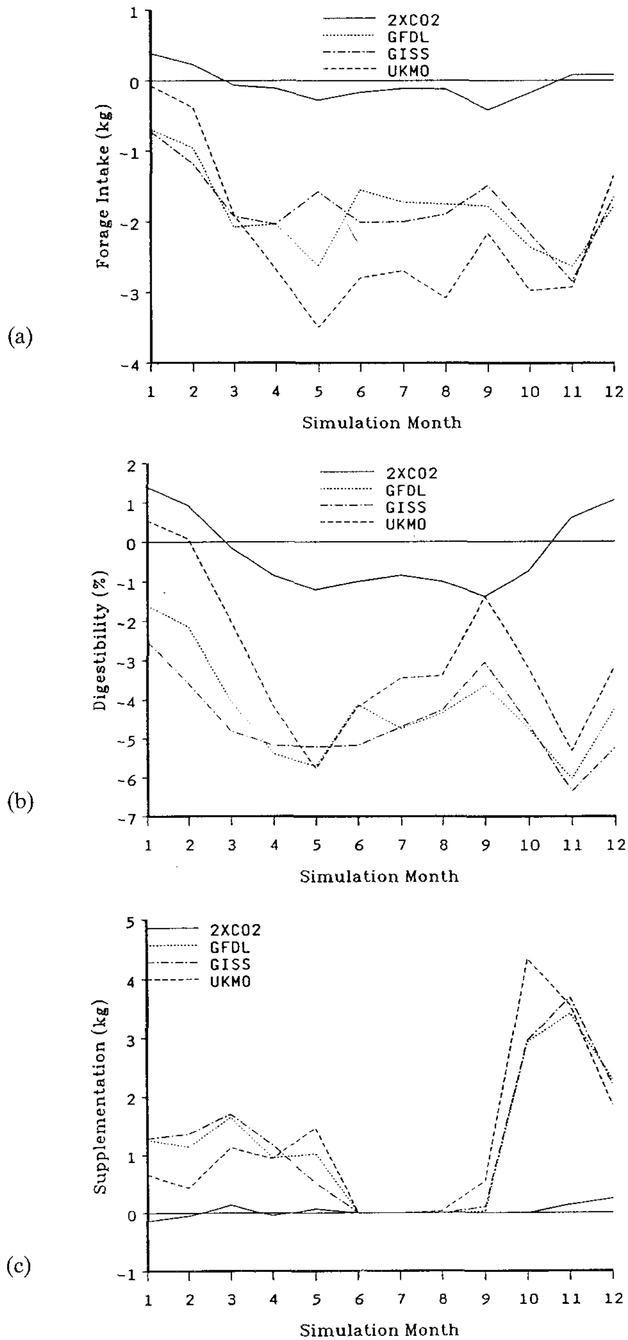


Fig. 7. (a) Changes in monthly means of 30 y simulation runs using four climate change scenarios for forage intake (kg). Representative site in MLRA 81 (TX). (b) Changes in monthly means of 30 y simulation runs using four climate change scenarios for digestibility (%). Representative site in MLRA 81 (TX). (c) Changes in monthly means of 30 y simulation runs using four climate change scenarios for supplementation (kg). Representative site in MLRA 81 (TX).

lists constantly modify their management practices to adapt to changing climatic conditions. Strategic options, in this case, include varying stocking rates, timing of grazing and genotype or species of grazers. The methodology in this study initiated an altered climate abruptly rather than the gradual change that would occur in a natural system. Despite these and other simplifying assumptions, the results are not without value.

The findings revealed that both animal and plant production in the northern regions were enhanced by the climate change scenarios. Two indicators directly affecting cow-calf range operation profitability, calf weaning weights and the F:S ratio showed large increases. To the extent that calves are sold and not retained, higher calf weaning weights would increase gross returns directly. Higher F:S ratios indicate less supplemental feeding and thus lower costs. These and other factors declined relative to the NOMINAL scenario in the southern Great Plains, suggesting reduced economic viability for range cattle livestock systems in this region.

Economic incentives would induce a nothward shift in the production of feeder calves from range-based cow-calf herds in the event of climate change. Derived incentives could lead to some relocation of the cattle feeding industry as well.

Reductions in soil organic matter in nothern regions raise questions of the long-term sustainability of the ecosystem. Organic matter losses could alter below-ground nutrient cycling and, thus, reduce above-ground plant production. Increased variability of plant production is also possible. As a result, present use of the ecosystem may not be sustainable under climate conditions simulated in this study. Below-ground processes need to be evaluated further to determine the potential long-term impact of climatic change on grassland ecosystems.

Increased variability in plant production, length of grazing season, and the amount of supplemental feed needed to get animals through the winter months resulted from the climate change scenarios. Since each of these factors will impact economic viability, the increased levels of variation could result in increased economic risk even with the potentially higher returns suggested for the northern regions. Further research is needed to examine the impact of variability from potential climate change on economic risk of cattle production.

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