Comparison of the Effects of Different Climate Change Scenarios on Rangeland Livestock Production

J. D. Hanson, B. B. Baker
USDA-ARS, Great Plains Systems Research, PO Box E, Fort Collins, Colorado 80522, USA

&

R. M. Bourdon
Department of Animal Sciences, Colorado State University, Fort Collins, Colorado 80523, USA

(Received 27 May 1991; revised version received 24 April 1992; accepted 28 April 1992)

ABSTRACT

The effect of climate change on plant and livestock production in the Great Plains of North America is an important issue. The purpose of this study was to modify an existing rangeland ecosystem model and to simulate a cow/calf production system under different climate scenarios. The project required the capability of simulating rangeland livestock production under different ambient CO$_2$ concentrations, temperatures and precipitation patterns. Climate change scenarios were created from three general circulation models (GCMs): GISS (Goddard Institute for Space Studies model), GFDL (Geophysical Fluid Dynamic Laboratory model), and UKMO (United Kingdom Meteorological Office model). Results from the GCMs were used to modify the climate record for a site in northeastern Colorado. Concomitantly, modifications were made to the SPUR model to help predict the effect of predicted climate change on selected variables of the range/livestock ecosystem. Simulation runs showed that predicted climate change will affect plant and animal production for rangelands. Changes in production were more closely related to changes in temperature and precipitation than to enhanced [CO$_2$] alone. The effect of climate change on livestock production was very complex and results were dependent on the particular GCM scenario being simulated.
INTRODUCTION

Many scientists are concerned that the burning of fossil fuels adds carbon dioxide ($\text{CO}_2$) to the atmosphere, which could cause the surface temperature of the earth to rise. Atmospheric $\text{CO}_2$ concentration has increased from 280 to 350 ppm over the last century. At present rates of increase, atmospheric $[\text{CO}_2]$ may double in the next 75 years compared to pre-industrial levels (Dickinson, 1989). Concentrations of other greenhouse gases (e.g. methane (CH$_4$), nitrous oxide (N$_2$O) and chlorofluorocarbon compounds (CFCs)) also appear to be increasing (Keeling et al., 1989; Rosenzweig, 1989). Though perhaps exaggerated (Nierenberg, 1990), these gases absorb thermal radiation which subsequently warms the earth's atmosphere. General circulation models (GCMs) suggest that the average global temperature will increase by as much as 3 to 5°C as atmospheric $\text{CO}_2$ levels double (Rosenzweig, 1989). GCMs also predict an increased rate of circulation in the global hydrologic cycle, which could lead to increased precipitation. However, GCMs cannot reliably predict regional-scale precipitation change—the vital information needed to estimate the potential impact of climate change on agricultural production.

The US Environmental Protection Agency, Office of Policy, Planning and Evaluation, was asked by US Congress to explore the implications of climate change (Smith & Tirpak, 1989). Yet, little is known concerning the potential effect of global warming on rangeland livestock production. The objective of this work was to assess the impacts of four climate change scenarios on livestock production for northeastern Colorado.

METHODS

Model description

SPUR (simulation of production and utilization of rangelands) is a general grassland ecosystem simulation model that includes components for the simulation of rangeland hydrology–plant–animal interactions (Wight & Skiles, 1987; Hanson et al., 1988). It can simultaneously simulate 15 plant species growing on up to 36 different sites. 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 a stochastic weather generator. Other abiotic variables required by the model include daily soil temperature, soil-water potential, ambient $[\text{CO}_2]$ and soil bulk density. The
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.

Evaporation and transpiration are calculated using the Ritchie (1972) equation. Potential evaporation ($E_o$) is computed as a function of daily solar radiation, mean air temperature, and albedo. Potential soil evaporation at the soil surface ($E_{so}$) is computed as a function of leaf area index (LAI) of the field and the amount of litter which covers the soil surface. Actual soil evaporation ($E_s$) is computed in two stages, based on the soil moisture status of the upper layer. Stage 1 evaporation is limited by energy—meaning that the soil profile is saturated and the process is dependent on the amount of solar radiation reaching the soil surface. Stage 2 evaporation is dependent on the movement of water to the soil surface and the amount of water in the soil profile; it is probably the more common of the two mechanisms in operation in the arid and semi-arid regions of the western USA. Potential plant transpiration ($E_{po}$) is calculated as a function of $E_s$ and LAI (when LAI < 3.0) or as a function of $E_o$ and $E_s$ (LAI > 3.0). If soil water is limited, plant transpiration ($E_p$) is computed as a function of $E_{po}$, soil water in the root zone and the field capacity. Solar radiation and the soil-surface area covered by above-ground biomass govern water loss from the soil profile.

The water balance used in SPUR for a single time step at a single point on a watershed is:

$$SW = SW_0 + P - (Q + ET + PL + QR)$$

where $SW$ is the current soil water content, $SW_0$ is the previous soil water content, $P$ is the cumulative precipitation, $Q$ is the amount of surface run-off, $ET$ is the cumulative amount of evapotranspiration, $PL$ is the cumulative amount of percolation loss to deep groundwater storage, and $QR$ is the cumulative amount of return flow (Renard et al., 1987).

For evaporation from the soil to occur, water must infiltrate through the soil surface and into the soil profile. Any soil water which is not lost to percolation, to root uptake, or to evaporation remains in the interstitial area between soil particles and is termed 'storage'. The process of infiltration reduces the amount of water available for overland flow component of run-off ($Q$) and increases the amount of water for evapotranspiration ($ET$) and for deep percolation ($PL$). Once water has percolated through
the root zone of the soil, it is essentially lost to this hypothetical single point of the watershed. Such percolated water may return to the surface down the slope as return flow to another point on the watershed or as flow into a channel. Otherwise, this water remains in an aquifer, but is not available for transpiration nor for evaporation. If precipitation occurs while air temperatures are below freezing, that moisture will not be available for any of the hydrologic processes mentioned above as it will be tied up in the snowpack. The consequence is a reduction in the effective precipitation for a given time step. This water may show up at a later time step once it melts and it will then be available for infiltration and for run-off.

The plant component of the SPUR model uses information from the ecosystem level model (ELM), developed by the US Grassland Biome Study (Innis, 1978), and grassland models developed by Parton et al. (1978) and Detling et al. (1979) (Hanson et al., 1988). The model simulates the flow of carbon and nitrogen through the soil–plant–animal continuum. There are seven carbon and eight nitrogen components in the model. Species-dependent state variables in the carbon and nitrogen sub-models are green shoots, live roots, propagules and standing dead. Dead roots, litter, soil inorganic nitrogen and soil organic matter are pooled across species. The model simulates competition between plant species and the impact of grazing on vegetation in response to various environmental variables.

The plant submodel was modified to account for increases in atmospheric [CO$_2$]. Elevated [CO$_2$] was assumed to only affect plant net photosynthetic rate. We subsequently assumed net photosynthesis will increase by 35% as CO$_2$ concentration doubles, the base ambient CO$_2$ concentration is 330 ppm and the intercellular CO$_2$ concentration is 70 ppm.

Recently, CBCPM (Colorado beef cattle production model), a second generation beef-cattle production model that was a modification of the Texas A & M beef model (Sanders & Cartwright, 1979), was linked with the SPUR model. CBCPM is a herd-wide, life cycle simulation model and operates at the level of the individual animal. The biological routines of CBCPM simulates animal growth, fertility, pregnancy, calving, death and demand for nutrients. Currently, 14 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, animal demand for 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.
SPUR has been subjected to numerous validation tests and investigative research. Richardson et al. (1987) successfully validated the weather generator. Renard et al. (1983) tested the hydrology module by conducting a 17-year (1965–81) simulation for two Arizona watersheds and obtained high correlations between observed and predicted run-off (0.878 and 0.941). Springer et al. (1984) used the hydrology component of SPUR to predict the hydrological response of three Idaho watersheds over a 5-year period ($r^2$ values ranged from 0.63 to 0.85); they concluded the model did a good job of simulating the timing and amount of monthly run-off, but this was a poor predictor of erosion and sedimentation. The snow accumulation and snowmelt components were tested in a watershed in southwest Idaho by Cooley et al. (1983). Using parameters derived from the 1980 snow season, they obtained a correlation of 0.91 between observed data from 1970–72 and 1977 and model predictions.

Skiles et al. (1983) simulated the growth of the two dominant grasses in the shortgrass steppe of Colorado and concluded that the SPUR plant growth module adequately reproduced the biomass production of the grasses and matched the dynamics of the growing season. In a test of the plant–animal interface, Hanson et al. (1988) showed that the SPUR model correctly predicted domestic animal weight gains as a function of stocking rate for a Colorado grassland (which is also an indirect validation of the plant module). SPUR has been successfully used to predict animal gains and plant biomass production on pastures in West Virginia (Stout et al., 1990), to provide simulated forage for a modified heifer module (Field, 1987) and to provide biomass to a grazing behavior model (Baker et al., 1992).

CBCPM is a new model and has yet to be thoroughly validated. However, most of the equations describing physiological and biological processes have been used and validated in previous models (Notter, 1977; Sanders & Cartwright, 1979; Bourdon, 1983; Bourdon & Brinks, 1987; 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).

Simulation runs

SPUR coupled with CBCPM was used to simulate 20 years of livestock production on a shortgrass prairie site in northeastern Colorado. The soil was parameterized as an Ascalon fine sandy loam. Plant production for a single site was simulated using the standard parameters for warm- and cool-season grasses, warm- and cool-season forbs, and shrubs (Hanson et al., 1988); total plant production was determined by
summing production estimates for the species group. Herd size was set to maintain 20 cows, calves and replacement heifers on 400 ha. Supplemental feed was provided to achieve a moderate body condition at calving.

Climate data for the 20-year nominal run were generated using CLIMGEN (Wight & Skiles, 1987). Effects of predicted climate change for the four scenarios were subsequently run and compared to the nominal run (NOMINAL). The climate-change scenarios we used were doubled CO₂ (2 × CO₂) and predictions from three GCMs: Goddard Institute for Space Studies model (GISS) (Hansen et al., 1983), Geophysical Fluid Dynamic Laboratory model (GFDL) (Manabe & Wetherald, 1987) and United Kingdom Meteorological Office model (UKMO) (Wilson & Mitchell, 1987). Predicted climate change data from the GCMs were obtained from the National Center for Atmospheric Research (NCAR).

Indicator variables

Indicator variables are model derived state or intermediate variables whose values are predicted by the simulation. For purposes of this study, we included soil organic matter, soil inorganic nitrogen, plant standing crop, total plant production and total plant nitrogen as plant production and quality indicator variables. Cow weight at weaning, average daily gain for cows, milk production, forage intake, quality of forage consumed (as determined by the nitrogen content of the forage), amount of supplementation and calf weaning weight were indicator variables for testing the effect of climate change on livestock performance.

Statistical analysis

Monthly means for each 20-year simulation were calculated. The nominal run and the four climate change scenarios were considered treatments. Standard analysis of variance was used to analyze for treatment differences. The treatment by year interaction mean square was used for the error term. The Scheffe's multiple-comparison procedure was used to test for significance on all main effects. Changes from nominal predictions were represented graphically for each of the indicator variables (Figs 3–8).

RESULTS AND DISCUSSION

Mean annual temperature was increased by 5.6, 4.9 and 6.3°C as predicted by GFDL, GISS and UKMO, respectively. Precipitation was increased for GISS and UKMO (2.34 and 5.79 cm year⁻¹, respectively)
Effects of climate change on rangeland livestock production

TABLE 1
Means and Coefficients of Variation (CV) for Selected Indicator Variables

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Precipitation (cm)</th>
<th>Plant production (kg/ha)</th>
<th>Calf weaning weight (kg)</th>
<th>Cow weaning weight (kg)</th>
<th>Average daily gain (kg/day)</th>
<th>Forage-to-supplement ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>35.41c</td>
<td>818.3c</td>
<td>192.2ab</td>
<td>587.7a</td>
<td>0.836a</td>
<td>2.99b</td>
</tr>
<tr>
<td></td>
<td>(16.2)d</td>
<td></td>
<td></td>
<td></td>
<td>(16.2)</td>
<td>(27.5)</td>
</tr>
<tr>
<td>2 × CO₂</td>
<td>35.41c</td>
<td>852.2c</td>
<td>188.8bc</td>
<td>570.9b</td>
<td>0.819b</td>
<td>2.59c</td>
</tr>
<tr>
<td></td>
<td>(16.2)</td>
<td></td>
<td></td>
<td></td>
<td>(16.2)</td>
<td>(27.4)</td>
</tr>
<tr>
<td>GFDL</td>
<td>32.69d</td>
<td>870.2bc</td>
<td>194.5a</td>
<td>574.6b</td>
<td>0.839a</td>
<td>4.65a</td>
</tr>
<tr>
<td></td>
<td>(16.9)</td>
<td></td>
<td></td>
<td></td>
<td>(16.9)</td>
<td>(35.8)</td>
</tr>
<tr>
<td>GISS</td>
<td>37.75b</td>
<td>972.5ab</td>
<td>188.1c</td>
<td>546.4c</td>
<td>0.815b</td>
<td>3.78ab</td>
</tr>
<tr>
<td></td>
<td>(16.2)</td>
<td></td>
<td></td>
<td></td>
<td>(16.2)</td>
<td>(24.8)</td>
</tr>
<tr>
<td>UKMO</td>
<td>41.20a</td>
<td>1037.9a</td>
<td>187.5c</td>
<td>531.0d</td>
<td>0.814b</td>
<td>3.66abc</td>
</tr>
<tr>
<td></td>
<td>(16.3)</td>
<td></td>
<td></td>
<td></td>
<td>(16.3)</td>
<td>(25.2)</td>
</tr>
</tbody>
</table>

a Values within a column followed by different letters are significantly different at α = 0.1.
b Calf weaning weight at 205 days of age.
c Cow weight at weaning.
d Values in parentheses are CV.

and decreased by 2.72 cm year⁻¹ for GFDL (Table 1). For the simulations, monthly patterns of temperature and precipitation were modified using data generated by the GCMs. GFDL showed the greatest increase in temperature during the summer months (Fig. 1(a)). GISS tended to have lower summertime temperature increases. The temperature increase as predicted by UKMO was the least variable throughout the year. GFDL predicted the lowest yearly rainfall, followed by GISS and UKMO. Monthly rainfall distribution was similar to NOMINAL for GISS and UKMO, but GFDL predicted decreased rainfall for the summer grazing months (Fig. 1(b)).

Plant production and quality

Climate change has great potential to modify plant production on rangeland. The factors that most affect rangeland plant production are temperature, precipitation and soil nitrogen. The interaction of these environmental factors with atmospheric [CO₂] is extremely complex. Based on the SPUR simulation, yearly plant production was not significantly increased by doubling CO₂ alone (2 × CO₂), but when CO₂ doubling was combined with changes in temperature, plant production increased significantly (Table 1).
Moisture accounted for the greatest amount of increase in production. GFDL predicted a temperature increase associated with an 8% decrease in precipitation. As a result, production increased by only 6% from the nominal run. However, as precipitation increased by 7 and 16% for GISS and UKMO, respectively, production increased significantly by 18 and 27%. Also, the coefficient of variation (CV) increased by 10% for GFDL, whereas slight decreases in CV occurred under the hot, wet regime (UKMO).

Increased production, however, is not the most important consideration for livestock production. In fact, the model predicts that if production is increased by changing growth parameters (maximum photosynthetic rate for example), but the amount of nitrogen assimilated remains unchanged or is reduced, then forage intake by grazing animals and subsequent gains will decrease. All of the scenarios, including $2 \times \text{CO}_2$, showed increases in standing green biomass (Fig. 2(a)), but the nitrogen concentration of those plants decreased considerably during the summer grazing months (Fig. 2(b)). These decreases are great enough to cause substantial decreases in animal performance.
Fig. 2. Changes in monthly means of 20-year simulation run using four climate change scenarios for (a) standing green biomass and (b) nitrogen content of standing green biomass.

Soil organic carbon and plant available inorganic nitrogen were also affected by the climate change scenarios. Soil organic carbon was generally lower for GFDL than for the nominal run. Increases in soil carbon were predicted for 2 × CO₂, GISS and UKMO (Fig. 3(a)). However, for most years, GFDL predicted increases in the amount of soil inorganic nitrogen (Fig. 3(b)).
Fig. 3. Changes in yearly means of 20-year simulation run using four climate change scenarios for (a) soil organic matter and (b) soil inorganic nitrogen content.

Animal performance

Animal production generally decreased with the climate change scenarios. Forage intake varied by month and scenario (Fig. 4). Increases in forage intake during the fall and winter months resulted from increases in standing crop. Increased ambient temperature (Fig. 1(a)) and decreased forage quality (Fig. 5) caused a decrease in the amount of forage con-
Fig. 4. Changes in monthly means of 20-year simulation run using four climate change scenarios for forage intake.

assumed during the summer months. Consequently, cow weights were significantly lower at weaning for all GCM and $2 \times \text{CO}_2$ runs (Table 1).

Mean average daily gain (ADG) over the year for both the nominal and GFDL simulations were significantly greater than the other scenarios (Table 1). ADG for cows decreased during the summer months for all GCM and doubled CO$_2$ simulations (Fig. 6). Increases in fall and early

Fig. 5. Changes in monthly means of 20-year simulation run using four climate change scenarios for digestibility of consumed forage.
winter supplementation caused an increase in ADG (Fig. 7). The forage-to-supplement ratio (FOR: SUPP) was the same for both the GISS and NOMINAL scenarios, while the UKMO scenario was not different from any other simulation (Table 1). Increased spring plant production (Fig. 2(a)) caused a subsequent reduction in the amount of supplement needed (Fig. 7). The CV for FOR: SUPP increased with all GCM simulations.
Although the climate change scenarios indicate that less supplement is needed, yearly variation in the amount and timing of supplementation is less certain. Calf weaning weights (Table 1) were higher, but not significantly different from the nominal run for the GFDL scenario due to higher milk production (Fig. 8) in the spring and higher forage digestibilities (Fig. 5) during the fall. Decreases in milk production and fall forage digestibilities were responsible for reduced weaning weights for all other scenarios. Only the GISS and UKMO runs were significantly different from the nominal run. Reproductive performance measured by percentage calf-crop was not significantly modified by the scenarios because the cows were supplemented to maintain body condition scores of 5.0 at calving.

CONCLUSIONS

Doubling [CO$_2$] alone did not significantly increase plant production. However, combining doubled [CO$_2$] with the predicted effect of temperature and precipitation elicited considerable change in plant and animal production. Moisture exhibited the most control over plant production. Also, the variance of the production estimates was different for different GCMs. Plant production for the GFDL scenario (hot, dry) was more variable than for the UKMO scenario (hot, wet). All of the scenarios predicted decreases in plant nitrogen content during the summer grazing
months. The GCMs also predicted an increased length of the growing season. The shortgrass prairie receives most of its moisture in spring. The summers are generally very dry. The GCMs seem to accentuate this pattern and as a result the growing season is longer (by some 30 days). Subsequently, production is increased, particularly in the spring (April) and fall (October).

The climate change scenarios caused decreases in animal production because of increased ambient temperature and decreased forage quality. As a result, cow weights at weaning were considerably lower. Increases in spring plant production allowed a reduction in the amount of supplement needed to sustain the animals. However, the CV for the FOR: SUPP increased for all GCM scenarios.

Increases in variance are important because of the effect such changes will have on grazing management. If the variance for yearly production does indeed increase, then uncertainty regarding plant growth increases, thereby resulting in uncertainty in management decisions. Using a 1-year time-step livestock production model, changes in variance typical of these simulations showed that carrying capacities must be dropped from about 6.5 to 9.0 ha per animal to maintain a 90% confidence of not overstocking.

Management of livestock will ultimately guide animal performance. In bad years the manager must either sell livestock or feed them. If vegetation production is more variable, then stocking rates must be decreased to insure good animal vigor. The more intense the management, the more the cost to the operator. Thus, even though the livestock may perform at similar levels, in the end, beef production costs may increase. The actual economics associated with the effect of climate change on livestock production will need further investigation.

ACKNOWLEDGMENTS

This research was conducted with funds from the US Environmental Protection Agency, Office of Policy, Planning and Evaluation, and the US Department of Agriculture, Agricultural Research Service.

REFERENCES

Effects of climate change on rangeland livestock production


