VULNERABILITY OF THE ASIAN TYPICAL STEPPE TO GRAZING AND CLIMATE CHANGE

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Abstract. The vulnerability of grassland vegetation in Inner Mongolia to climate change and grazing was examined using an ecosystem model. Grazing is an important form of land use in this region, yet there are uncertainties as to how it will be affected by climate change. A sensitivity analysis was conducted to study the effects of increased minimum and maximum temperatures, ambient and elevated CO_2, increased or decreased precipitation, and grazing on vegetation production. Simulations showed that herbaceous above ground net primary production was most sensitive to changes in precipitation levels. Combinations of increased precipitation, temperature, and CO_2 had synergistic effects on herbaceous production, however drastic increases in these climate scenarios left the system vulnerable to shifts from herbaceous to shrub-dominated vegetation when grazed. Reduced precipitation had a negative effect on vegetation growth rates, thus herbaceous growth was not sustainable with moderate grazing. Shifts in temporal biomass patterns due to changed climate have potentially significant implications for grazing management, which will need to be altered under changing climate to maintain system stability.

1. Introduction

Understanding the vulnerability of ecosystems to global change is becoming increasingly important as the effects of climate change are surfacing. It is well recognized that atmospheric changes have occurred worldwide, including increased CO_2 (Keeling et al., 1995; IPCC, 1996; Watson et al., 1996; Diaz et al., 1998; IPCC, 2001), increased temperatures (Karl et al., 1993; IPCC, 1996; Smit and Yunlong, 1996; IPCC, 2001), and changed precipitation patterns (Fu and Wen, 1999; Smit and Yunlong, 1996; Zhai et al., 1999; IPCC, 2001). Although large-scale climate changes have occurred, changes are predicted to differ depending on regional location. For example, increased winter temperatures and decreased precipitation patterns are only predicted in central and northern China (Smit and Yunlong, 1996; Polley et al., 2000).

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Multiple studies have been conducted to examine the effects of localized climate changes on vegetation processes, and the scientific community recognizes the importance of adding grazing to this equation (Baker et al., 1993; Thornley and Cannell, 1997; Diaz et al., 1998; Hall et al., 1998; Reido et al., 2000; Ludwig et al., 2001). A significant obstacle to assessing grazing effects is the difficulty of conducting experiments at a large enough scale. Experiments have been conducted in chambers or sample plots to examine the interactive effects of climate change and grazing by insects or by clipping (Newton et al., 1995; Diaz et al., 1998), but few studies have explored the interactions of climate change and livestock grazing at larger scales (Baker et al., 1993; Panario, 1997). Grazing plays a significant role in ecosystem function (Watson et al., 2000), therefore it is important to include grazing in studies of ecosystem responses to climate change (Polley et al., 2000).

Native grasses of the typical steppe, defined as a bunch-grass steppe with many or few forbs in a semi-arid climate (Lavrenko and Karamysheva, 1993; Zhu, 1993), are well adapted to herbivory and have supported grazing as the dominant land use for thousands of years. A change in climate could affect this tightly coupled system, disrupt the balance between grazers and vegetation, and have negative effects on the people who use them (Alward et al., 1999). For these reasons, it is important to better understand interactions between climate change and grazing, to prevent overgrazing and to maintain viable grazing systems. To best analyze climate-grazing interactions, it is vital to simultaneously consider ecosystem components, such as vegetation, soil, and livestock (Allen-Diaz, 1996).

The objective of this study was to assess potential effects of climate change and grazing on the typical steppe grasslands using the SAVANNA ecosystem model (Coughenour, 1993). A factorial experiment involving precipitation, temperature, and CO_2 was conducted to explore grazing system sustainability under climatic change scenarios.

2. Methods

2.1. STUDY AREA

The typical steppe region of Inner Mongolia, China extends across 41° to 47° north latitude and 109° to 117° east longitude. This study was focused on the Baiinxile Livestock Farm located at 43.5° north latitude and 116.5° east longitude within the typical steppe. The farm is 3,680 km^2, divided into an administrative village and 12 branches. A branch is an administrative division of land, ranging in size from 79 to 655 km^2. This landscape consists of large rolling hills, with elevation ranging from 963 to 1569 m. The typical steppe is dominated by C_3 grasses, which include *Leymus chinensis* and *Stipa grandis* (Li, 1978). Important forb and shrub species include *Artemisia frigida* and *Caragana microphylla* (Zhu, 1993). The grasses in this region have coexisted with native and domestic grazers for thousands of years and are therefore likely to be well adapted to grazing.

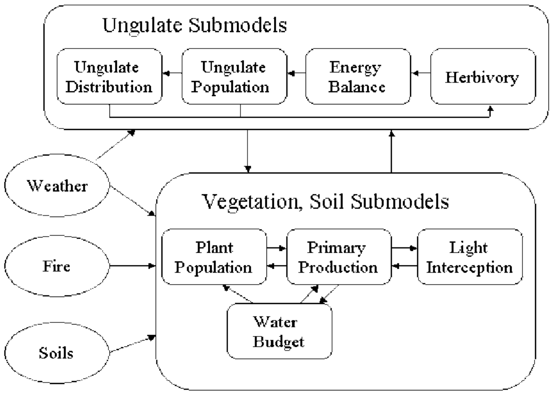

Figure 1. SAVANNA model structure (Coughenour, 1993).

Mean annual temperature is –0.4 °C with extremes ranging from –27.0 to 28.6 °C (Li, 1989; Xiao et al., 1997). Long term mean annual precipitation is 360 mm but varies between 180 and 500 mm. Because the majority of precipitation occurs during the growing season, biomass production is high as compared to other regions with similar amounts of rainfall but with smaller proportions received during the growing season.

2.2. MODEL DESCRIPTION

The SAVANNA model (Coughenour, 1993) used in this analysis is a spatially explicit, dynamic, simulation model that represents ecosystem processes at both local and regional scales. Ecosystem processes are modeled by using data on soils, topography, climate, and livestock densities to affect vegetation production and cover, livestock forage utilization, livestock production, and human offtake (Figure 1). SAVANNA is process-based, representing flows of biomass, nitrogen, and organisms, and subsequent rates of change in system states. Its one-week time step enables large-scale spatial and long-term temporal simulations. These capabilities enable simulations of interactive responses to climate and grazing.

SAVANNA has successfully been parameterized and used to simulate vegetation and ungulate production in a wide variety of ecosystems such as Rocky Mountain National Park, Colorado (Weisberg and Coughenour, 2003); Yellowstone National Park, Wyoming (Coughenour and Singer, 1996a,b); Kajiado District, Kenya (Boone et al., 2001); Northern Australia (Ludwig et al., 2001); Ngorongoro Conservation Area, Tanzania (Boone et al., 2002); Kruger National Park, South Africa (Kiker, 1998) and Inner Mongolia, China (Christensen et al., 2003).

A detailed description of the SAVANNA parameterization and validation for this study site can be found Christensen et al. (2003). Fieldwork was used to parameterize the vegetation and soil portions of the model (Xiao et al., 1996; Christensen et al., 1998) including vegetation biomass and percent cover data.

Information for livestock parameters, including height, weight, and diet were gathered from data specific to the Typical steppe (weight of adult sheep, horse, and cow = 75, 386, and 600 kg respectively) (Yang, 1987). Herbaceous plants were selected as the preferred forage type due to the overall dominance of grass and forbs in this ecosystem (personal communications with herders). Predicted green leaf biomass amounts were validated using 11 years of Normalized Difference Vegetation Index bimonthly composites derived from satellite imagery (Tucker, 1979; Justice et al., 1985; Malingreau, 1986). Correlations between observed and predicted values ranged from $R^2 = 0.34$ to $R^2 = 0.57$ ($P < 0.001$) (Christensen et al., 2003).

The model was modified to represent CO_2 effects on photosynthesis and transpiration. Under doubled CO_2 (700 ppm) stomatal conductance and transpiration rates were reduced by 20%, while photosynthesis rates were increased by 20%. Conservative rather than maximum values were chosen based on field information (Jackson et al., 1994, 1998; Wand et al., 1999; J. Morgan, personal communication) because the modeled CO_2 effect was constant, and not dependent on time of day or season. The CO_2 response increased water use efficiency (*WUE*) and soil water, which could further affect plant growth (Knapp et al., 1996). The Penman–Monteith equation (Penman, 1953; Monteith, 1965) calculates canopy-scale transpiration, driven by temperature, radiation, and humidity. This formulation represents plant physiologically-mediated response to climate change by using temperature, radiation, and vapor pressure deficit as well as stomatal conductance to predict water loss from leaves. In the Penman–Monteith formula, an increase in temperature increases vapor pressure deficit, which results in an increase in transpiration rate. Stomatal conductance is differentially affected by temperature and relative humidity following Ball (1988). The interactions between climate, CO_2, and grazing are non-linear. Plant growth is an outcome of photosynthetic rate per unit leaf area, multiplied by leaf area index (LAI). It is non-linear response due to this multiplicative interaction. The effects of grazing on LAI, and the effects of CO_2 on photosynthetic rates, can therefore interact non-linearly.

2.3. EXPERIMENTAL DESIGN

Three simulation experiments were conducted to examine temperature, precipitation, CO_2, and grazing effects on grassland vegetation. The first two experiments examined the sustainability of a grassland system impacted with different climate change scenarios (*CC*) (Riedo et al., 1997) including increased temperature, precipitation changes, and moderate grazing. Moderate grazing was defined as 39 animal units (*AU*) km^{-2}. This value was based on previous results (Christensen et al., 2003) as the maximum number of animals that could be supported by herbaceous vegetation in this region while maintaining a sustainable system of grazing and herbaceous biomass production. Higher animal densities resulted in degradation. The model averages animal units over the entire simulated area, so at any particular moment, some areas could have a higher number of specified animals, whereas others could have fewer.

Experiment one was a sensitivity analysis, which used a factorial design with two temperature levels, three precipitation levels, and moderate grazing. Minimum and maximum temperatures were increased 2 and 0 °C respectively (T_{+2+0}), then 5 and 1 °C (T_{+5+1}) respectively. Precipitation levels included 80, 100 and 120% of actual precipitation data (P_{80}, P_{100}, P_{120}). Experiment two was a factorial design, which followed the same design as experiment one, but with doubled CO_2 (700 ppm (C_{2x})).

A third experiment was conducted where moderate grazing was replaced with light grazing from the first two experiments. The purpose was to examine the importance of grazing management when the combination of moderate grazing and climate change resulted in vegetation decline. Light grazing was defined in a previous study (Christensen et al., 2003) as 18 *AU* km^{-2}, the maximum number of animals per km^{-2} (within a range of 6 to 18 *AU*) that resulted in only slight decreases in herbaceous production.

Each experiment consisted of model runs 50 years in length. Eighteen years of local climate data were available from the area being simulated. To create 50 years of data, years were selected randomly from the 18 to create 32 more years (Figure 2). For climate change scenarios, precipitation days and temperatures were altered uniformly within each year, i.e., climate was not varied intra-annually. Thus each monthly input of temperature was increased and each monthly input of precipitation data was increased or decreased by 20%. The output variables used in the analyses were herbaceous and shrub above ground net primary production ($ANPP_h$ and $ANPP_s$).

3. Modeling Results

3.1. EXPERIMENT 1

Combinations of ambient and increased temperatures (t_a, T_{+2+0}), ambient and increased precipitation (P_{100}, P_{120}), and moderate grazing had varying effects on $ANPP_h$, but these combinations maintained a sustainable level of herbaceous biomass (Table I). A T_{+2+0} increase in temperature increased $ANPP_h$ by 3%, from 154 g m^{-2} y^{-1} with ambient temperature and precipitation ($T_a P_{100}$) to 158 g m^{-2} y^{-1} (values are averaged for the 50 years simulation run). Adding a 20% increase in precipitation ($T_{+2+0} P_{120}$) resulted in a 38% increase in $ANPP_h$ compared to a 39% increase with $T_a P_{120}$.

Climate change scenarios (*CC*) with a 20% reduction in precipitation, ambient and elevated temperatures (T_a, T_{+2+0}), and moderate grazing resulted in herbaceous productivity initially following precipitation patterns in the first 12 years, but in an overall decrease in herbaceous productivity. The *CC* of ambient temperatures at 80% precipitation ($T_a P_{80}$) and increased temperature at 80% precipitation

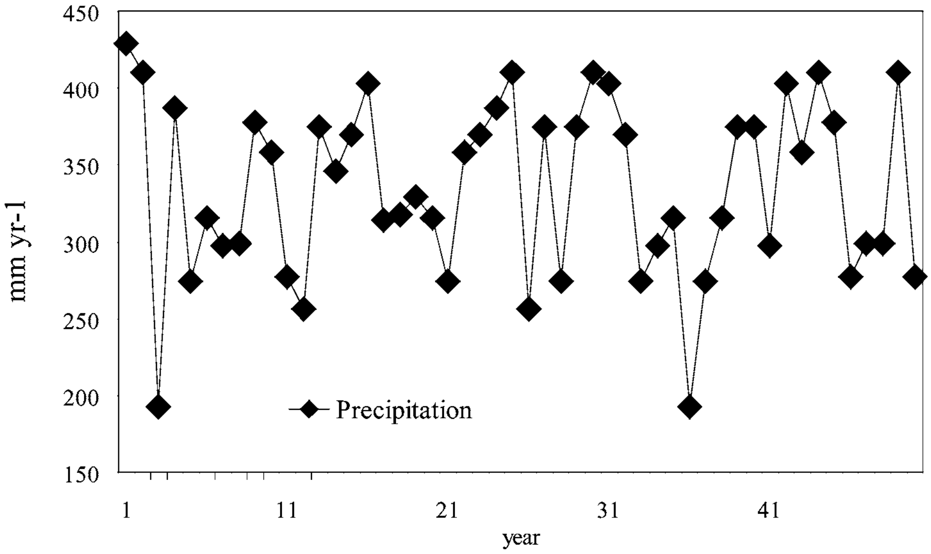

Figure 2. Annual precipitation (mm) for 50-year simulation run.

Table I

Herbaceous above ground net primary production (g m^{-2} yr^{-1}) responses to ambient and elevated CO_2 (μmol mol^{-1}), increased temperature (°C), precipitation (*Ppt*) change (% of ambient), and moderate grazing (29 *AU* km^{-2}) from experiments 1 and 2. Values are averaged over 50-year simulation.

Ppt (%)	Temperature (°C)		350 μmol mol^{-1} CO_2 (Exp. 1)	700 μmol mol^{-1} CO_2 (Exp. 2)
	ΔT_{min}	ΔT_{max}		
80	**0**	**0**	34.6	130.7
	2	**0**	29.7	120.5
	5	**1**	22.3	34.4
100	**0**	**0**	**153.9**	186.9
	2	**0**	158.2	187.4
	5	**1**	30.8	183.3
120	**0**	**0**	214.0	239.4
	2	**0**	212.6	240.3
	5	**1**	142.0	211.2

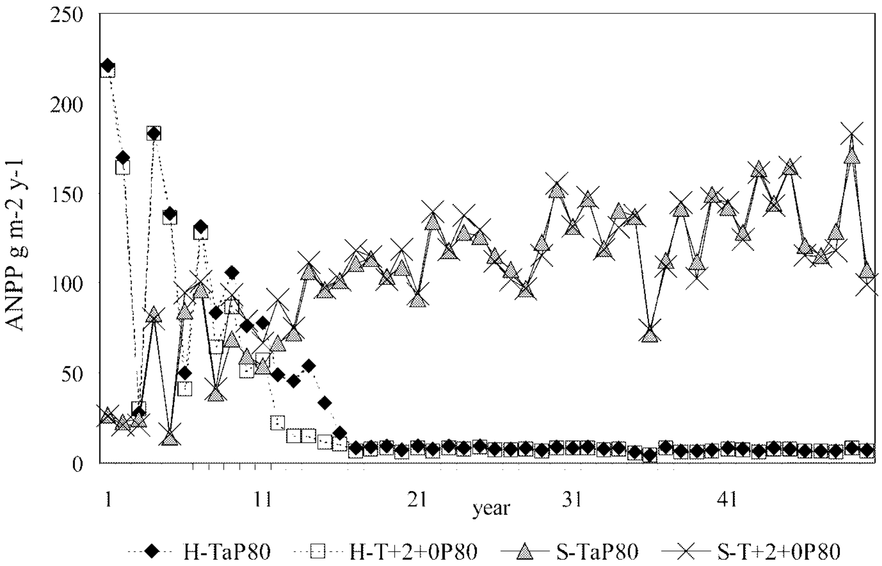

Figure 3. Herbaceous (H) and shrub (S) above ground net primary production from 50-year simulation runs with ambient and increased temperature (T_a, T_{+2+0}), and 80% precipitation (P_{80}), and moderate grazing.

($T_{+2+0}P_{80}$) reduced $ANPP_h$ by an average of 78 and 81% respectively. Shrub above ground net primary production ($ANPP_s$) increased in response to decreased $ANPP_h$. Shrubby vegetation was not browsed, so it expanded as $ANPP_h$ declined and competition with herbs decreased (Figure 3).

Combinations of T_{+5+1}, all precipitation levels, and moderate levels of grazing had greater impacts on $ANPP_h$ than the smaller temperature increase. A large temperature increase T_{+5+1} ($T_{+5+1}P_{100}$) in combination with moderate grazing reduced $ANPP_h$ catastrophically to an average of 30.8 g m^{-2} y^{-1} (Table I). When precipitation was increased by 20% ($T_{+5+1}P_{120}$), $ANPP_h$ still decreased but much less, from 153.9 g m^{-2} y^{-1} to 142.0 g m^{-2} y^{-1}. Reduction in precipitation (CC of $T_{+5+1}P_{80}$) decreased $ANPP_h$ by an average of 86% from T_aP_{100}. There was a rapid increase of shrubs due to shrub access to water in deep soil layers and lack of browsing of the shrub vegetation (Figure 4). The dramatic increase in shrub production with increased temperature and precipitation ($T_{+5+1}P_{120}$) occurred after a two year period with below average precipitation. Shrubs were able to capitalize on available resources and gain a competitive advantage over herbaceous production grazed with moderate levels of grazing during these low precipitation years.

3.2. EXPERIMENT 2

Elevated CO_2 with ambient precipitation, all temperature levels, and moderate grazing resulted in increases in $ANPP_h$. Both herbaceous and shrub production increased with doubled CO_2, due to increased water use efficiency and soil water

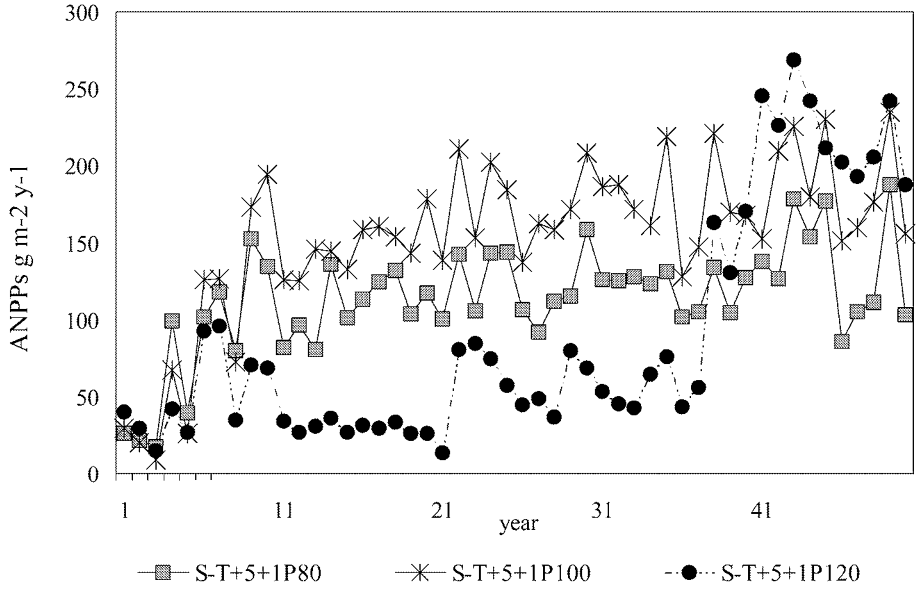

Figure 4. Shrub (*S*) above ground net primary production from 50-year simulation runs with increased temperature (T_{+5+1}), 80, 100 and 120% ambient precipitation (P_{80}, P_{100}, P_{120}), and moderate grazing.

(Figure 5). The $T_a P_{100} C_{2x}$, $T_{+2+0} P_{100} C_{2x}$, and $T_{+5+1} P_{100} C_{2x}$ scenarios resulted in 21, 22 and 19% increases in $ANPP_h$ respectively (Table I). When precipitation was increased by 20%, there were much larger increases in $ANPP_h$. *CC* of $T_a P_{120} C_{2x}$, $T_{+2+0} P_{120} C_{2x}$, and $T_{+5+1} P_{120} C_{2x}$ resulted in 56, 56 and 37% increases in $ANPP_h$ respectively. A doubling of CO_2 did not ameliorate the effect of a 20% decrease in precipitation and moderate grazing on plant production, and $ANPP_h$ decreased in all *CC* scenarios. The $T_{+5+1} P_{80} C_{2x}$ scenario resulted in a 78% decrease in $ANPP_h$. *CC* of $T_a P_{80} C_{2x}$ and $T_{+2+0} P_{80} C_{2x}$ resulted in a gradual decrease in $ANPP_h$ but no shift in vegetation composition (Figure 6).

3.3. EXPERIMENT 3

A decrease in grazer density reversed declines in $ANPP_h$ and maintained a sustainable level of herbaceous biomass production. When grazing was reduced from moderate to light with *CC* of $T_{+5+1} P_{120}$, average $ANPP_h$ increased to 228.2 g m^{-2} y^{-1} as compared to 142.0 g m^{-2} y^{-1} with a moderate grazing density (Table II). The $T_{+5+1} P_{100}$ scenario and light grazing was also sustainable, with an average of 170.1 g m^{-2} y^{-1} (Figure 7). Light grazing and $T_a P_{80} C_{2x}$, $T_{+2+0} P_{80} C_{2x}$, $T_{+5+1} P_{80} C_{2x}$, $T_a P_{80}$, and $T_{+2+0} P_{80}$ scenarios were sustainable for the 50-year simulation run with an average $ANPP_h$ of 151.3 g m^{-2} y^{-1}, 149.4 g m^{-2} y^{-1}, 135.9 g m^{-2} y^{-1}, 129.7 g m^{-2} y^{-1}, and 117.6 g m^{-2} y^{-1} respectively, but $ANPP_h$ values gradually decreased over the simulation period. Light grazing in combination with

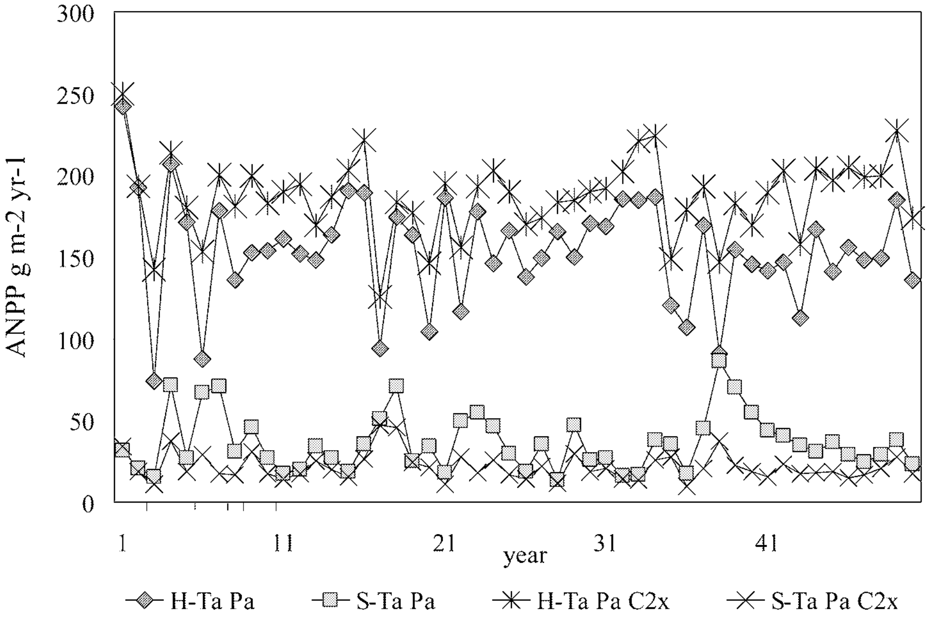

Figure 5. Herbaceous (H) and shrub (S) above ground net primary production with ambient and elevated CO_2 from 50-year simulation runs with ambient temperature (T) and precipitation (P) and moderate grazing.

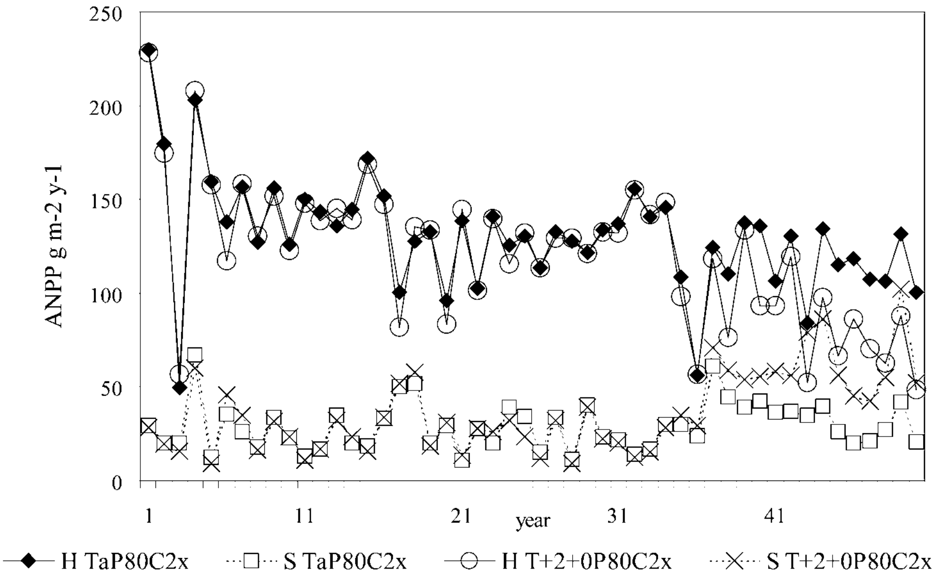

Figure 6. Herbaceous (H) and shrub (S) *ANPP* from 50-year simulation runs with ambient and increased temperature (T_a, T_{+2+0}), 80% precipitation (P_{80}), elevated CO_2 (C_{2x}), and moderate grazing.

Table II

Herbaceous above ground net primary production (g m^{-2} yr^{-1}) responses to ambient and elevated CO$_2$ (μmol mol^{-1}), increased temperature (°C), precipitation (*Ppt*) change (% of ambient), and light grazing (18 *AU* km^{-2}) from experiment 3. Values are averaged over 50-year simulation.

Ppt (%)	Temperature (°C)		350 μmol mol^{-1} CO$_2$ (Exp. 1)	700 μmol mol^{-1} CO$_2$ (Exp. 2)
	$\Delta T_{\min}$	$\Delta T_{\max}$		
80	**0**	**0**	129.7	151.3
	2	**0**	117.6	149.4
	5	**1**	42.1	135.9
100	**0**	**0**	–	–
	2	**0**	–	–
	5	**1**	170.1	–
120	**0**	**0**	–	–
	2	**0**	–	–
	5	**1**	228.2	–

CC $T_{+5+1}P_{80}$ was not sustainable and *ANPP*$_h$ production was reduced to 42.1 g m^{-2} y^{-1}. The system was unable to maintain herbaceous growth with decreased precipitation despite the reduction in grazing density.

4. Discussion

Simulations showed that *ANPP*$_h$ in this grazing ecosystem was most sensitive to changes in precipitation levels. However combinations of precipitation, temperature, and CO$_2$ had synergistic effects on herbaceous production. Increases in precipitation had larger positive effects on *ANPP*$_h$ than a doubling of CO$_2$, while small increases in temperature only had minimal effects. Greater increases in temperature put a larger stress on the plants, resulting in declining *ANPP*$_h$ unless increased precipitation, CO$_2$, or the combination of the two ameliorated the effects of the large increase in temperature. Because net primary production in this region is water limited, sufficient soil moisture was necessary for grasses to recover from grazing.

Reduced precipitation caused a decline in *ANPP*$_h$, so that moderate grazing of 39 *AU* km^{-2} could not be sustained in this modeling experiment. A decrease

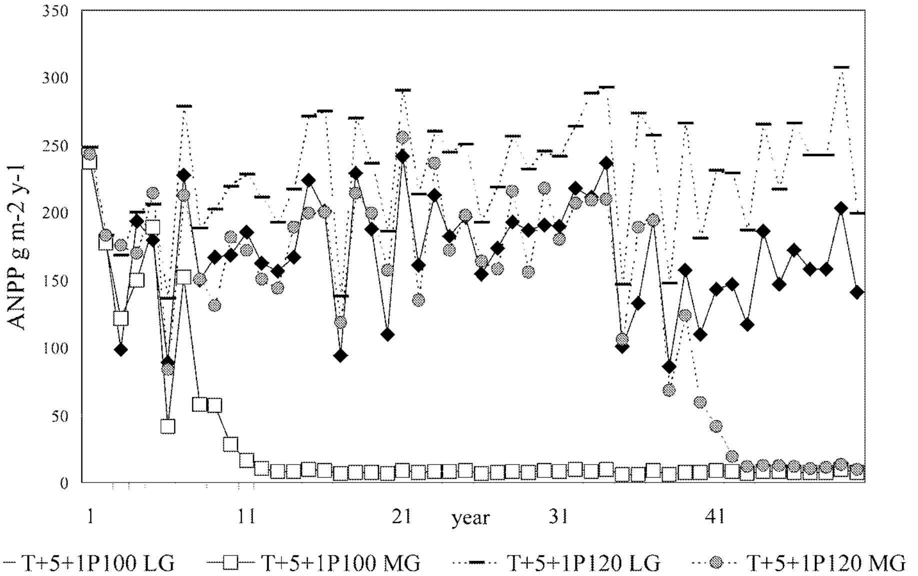

Figure 7. Herbaceous above ground net primary production ($ANPP_h$) in response to increased temperature (T_{+5+1}), and precipitation (P_{100}, P_{120}) change (% of ambient) with light grazing ($LG = 18$ AU km^{-2}) for 50-year simulation runs. $ANPP_h$ also reported for these climate change scenarios with moderate grazing (MG).

in precipitation resulted in lower soil water, which decreased plant growth rates. Lower growth rates were not sufficient for herbaceous plants to respond from grazing and shrubs were able to capitalize on available resources once the herbaceous vegetation was suppressed (Archer, 1996). Because shrubs were not browsed they displaced the overgrazed herbaceous plants and became the dominant functional group. Doubling CO_2 partially ameliorated the effects of reduced precipitation as a result of increased *WUE*. A doubling of CO_2 caused a decrease in stomatal conductance and increased photosynthesis; therefore *WUE* increased, which in turn increased plant growth in this water-limited system. The CO_2 effects allowed grazed grasses to remain competitive relative to unbrowsed shrubs despite a decrease in water.

Modeling experiments showed the system could not maintain a 50-year sustainable level of herbaceous biomass when subject to certain grazing and climate patterns; thus it was vulnerable to a shift from herbaceous to shrub-dominated vegetation. Shrub growth was limited because grasses limit water availability to shrubs with their intensive fibrous root structure (Köchy and Wilson, 2000; Polley et al., 2000; Brown et al., 1998). Decreased precipitation in combination with grass removal from grazing and lack of shrub browsing allowed shrub encroachment. It is important to note this system was dominated by grazers, including sheep, horses, and cattle. If goats, which browse shrubs, were simulated then the results would be different. These vegetation changes due to grazing and climate change are similar to threshold state changes typical of non-linear systems. It is important to recognize the potentials for vegetation shifts with climate change because they can lead to permanent and sudden ecological changes with little forewarning. Managers need to monitor livestock offtake to reduce system vulnerability under such scenarios of climatic change.

Previous models have projected increased grassland production under elevated CO_2 (Parton et al., 1995; Coughenour and Chen, 1997; Gao and Zhang, 1997; Neilson et al., 1998) although some of these models did not incorporate direct CO_2 effects on photosynthesis. Coughenour and Parton (1997) used the mechanistic GRASS-CSOM model and found elevated CO_2 at ambient and increased precipitation levels resulted in a 20–70% increase in C_3 grassland production. Wand et al. (1999) in a meta-analysis concluded grass biomass on average increased by 44% with elevated CO_2. While biomass could not be directly related to production, the trends in both show increases. A simulation study conducted by Gao and Zhang (1997) predicted an overall 15% increase in vegetation production with doubled CO_2 in the northeast region of China. However, responses of specific sites to elevated CO_2 differed with 26 and 61% increases in net primary production (NPP) in *Stipa baicalensis* steppe and *Aneurolipidium chinense* steppe grasslands, respectively. The combination of doubled CO_2 and increased precipitation and temperature caused a 24% decrease in vegetation production in the *Aneurolipidium chinense* steppe while it increased NPP by 44% in the *Stipa baicalensis* steppe. Decreases were due to larger temperature effects on the *Aneurolipidium* steppe than the *Stipa* steppe (Gao and Yu, 1998). SAVANNA was not parameterized to simulate differences in these species to elevated CO_2 or temperature.

This modeling experiment explored the possible implications of temperature, precipitation, and CO_2 changes for grazing management of the grasslands in Northeast Asia. A small increase in temperature, with increased CO_2 and decreased precipitation is likely to occur in this region within the next hundred years (Keeling et al., 1995; Smit and Yunlong, 1996; Giorgi et al., 1998; Polley et al., 2000; Watson et al., 2000; IPCC, 2001). The simulation model estimates a 22% decrease in $ANPP_h$ under such a climate regime and moderate grazing. To maintain ecosystem states it would be necessary to decrease livestock numbers in proportion to the decrease in forage production (Coughenour and Chen, 1997).

A second implication is the possible shift of vegetative state due to climatic change and grazing. Many rangelands exist in areas with variable climate patterns. Therefore, small shifts in climate could increase system vulnerability to vegetation state change (Rietkerk and van de Koppel, 1997; Ludwig et al., 2001). Rietkerk and van de Koppel (1997) give a mechanistic explanation of grazing induced shifts in vegetative stable states. They used a model to show how a loss in plant growth with heavy grazing resulted in a decrease in soil water due to higher run-off and decreased percolation. Lower soil water subsequently decreased plant production, so resources were insufficient to sustain production while being grazed. They found semi-arid systems are vulnerable to threshold effects and are thus fragile, when resources have reached these low levels. Results here are consistent with that conclusion.

With expanding human populations, there are increased pressures on rangelands for their resources (Polley et al., 2000). The typical steppe region is particularly vulnerable because it is currently experiencing climate change and an increasing trend in human and livestock population densities coupled with increased sedentarization. This intensified form of land-use could have disastrous effects with climate change (Archer, 1995). Models have been used to address the effects of grazing and climate on land use processes (Parton et al., 1987; Hanson et al., 1988; Thornley and Verberne, 1989; Hunt et al., 1991; Coughenour and Chen, 1997; Thornley and Cannell, 1997; Hall et al., 1998; Riedo et al., 2000; Ludwig et al., 2001) but there remain many unanswered questions (Nosberger et al., 2000). Studies are only beginning to analyze how livestock based agriculture will change due to shifts in climate patterns (Parsons et al., 2001).

Model simulations from this analysis give detailed insight as to which climate change scenarios had the greatest impact on changes in biomass. Grassland ecosystems are vulnerable to climate change and will likely experience increases or decreases in plant production. But more importantly, climate change can destabilize grazing ecosystems if not managed properly. Systems that would otherwise remain unsustainable under increased temperatures and decreased precipitation can maintain their stability if livestock grazing densities are adjusted.

5. Memorial

Dr. James Ellis was unfortunately unable to see the completion of this work due to his untimely death in March of 2002. With this paper, we would like to honor the efforts Dr. Ellis made with his research accomplishments in the Inner Mongolia region and would like to recognize his preeminent work on understanding the integration of humans and natural processes in arid ecosystems globally. We will miss him greatly.

Acknowledgements

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Nomenclature

CC	climate change scenarios
$T_a P_{100}$	ambient temperature, ambient precipitation
$T_a P_{100} C_{2x}$	ambient temperature, ambient precipitation, doubled CO_2
$T_a P_{80}$	ambient temperature, 80% precipitation
$T_a P_{80} C_{2x}$	ambient temperature, 80% precipitation, doubled CO_2
$T_a P_{120}$	ambient temperature, 120% precipitation
$T_a P_{120} C_{2x}$	ambient temperature, 120% precipitation, doubled CO_2
$T_{+2+0} P_{100}$	increase minimum temperature by 2 °C, max by 0 °C, ambient precipitation
$T_{+2+0} P_{100} C_{2x}$	increase minimum temperature by 2 °C, max by 0 °C, ambient precipitation, doubled CO_2
$T_{+2+0} P_{80}$	increase minimum temperature by 2 °C, max by 0 °C, 80% precipitation
$T_{+2+0} P_{80} C_{2x}$	increase minimum temperature by 2 °C, max by 0 °C, 80% precipitation, doubled CO_2
$T_{+2+0} P_{120}$	increase minimum temperature by 2 °C, max by 0 °C, 120% precipitation
$t_{+2+0} P_{120} C_{2x}$	increase minimum temperature by 2 °C, max by 0 °C, 120% precipitation, doubled CO_2
$T_{+5+1} P_{100}$	increase minimum temperature by 5 °C, max by 1 °C, ambient precipitation
$T_{+5+1} P_{100} C_{2x}$	increase minimum temperature by 5 °C, max by 1 °C, ambient precipitation, doubled CO_2
$T_{+5+1} P_{80}$	increase minimum temperature by 5 °C, max by 1 °C, 80% precipitation
$T_{+5+1} P_{80} C_{2x}$	increase minimum temperature by 5 °C, max by 1 °C, 120% precipitation, doubled CO_2
$T_{+5+1} P_{120}$	increase minimum temperature by 5 °C, max by 1 °C, 120% precipitation
$T_{+5+1} P_{120} C_{2x}$	increase minimum temperature by 5 °C, max by 1 °C, 120% precipitation, doubled CO_2

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