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Sensitivity of Inner Mongolia grasslands to climate change

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Abstract. We investigated the effects of global climate change and doubled atmospheric CO_2 concentration to plant primary production and soil organic matter of typical steppe (*Leymus chinense* steppe and *Stipa grandis* steppe) and meadow steppe (*Filifolium sibiricum* steppe, *S. baicalensis* steppe and *L. chinense* steppe) at individual sites in Inner Mongolia, using the CENTURY ecosystem model.

In the simulation of climate change, loss of soil organic C ranges from 783 $gC.m^{-2}$ in meadow steppe to 1485 $gC.m^{-2}$ in typical steppe, and annual above-ground net primary production (ANPP) decreases by 17.6 $gC.m^{-2}$ in meadow steppe to 29.5 $gC.m^{-2}$ in typical steppe under CCC (Canadian Climate Center). While under GFDL (Geophysical Fluid Dynamics Laboratory), loss of soil organic C varies from 584 $gC.m^{-2}$ in typical steppe to 1164 $gC.m^{-2}$ in meadow steppe, and ANPP decreases in the range of 18.3 $gC.m^{-2}$ in typical steppe to 32.1 $gC.m^{-2}$ in meadow steppe.

In the simulations of climate change plus elevated CO_2 (from 350 p.p.m. to 700 p.p.m.), ANPP decreases by 5.4 $gC.m^{-2}$ in meadow steppe to 11.3 $gC.m^{-2}$ in typical steppe under CCC + CO_2, while ANPP varies from an increase of 1.8 $gC.m^{-2}$ in *S. grandis* steppe to a decrease of 20.6 $gC.m^{-2}$ in meadow steppe under GFDL + CO_2. Losses of soil organic C are slightly lower (in the range of 42 $gC.m^{-2}$ to 248 $gC.m^{-2}$) than losses of soil organic C under climate change only.

These five steppe ecosystems are very sensitive to climate change, dependent upon projected change in temperature and precipitation by GCMs of CCC and GFDL.

Key words. Carbon, primary production, soil organic matter, natural grasslands

INTRODUCTION

Grassland in Inner Mongolia, China is very extensive and its total area reaches about 792,000 km^2 (Li & Chen, 1987; Zhang, 1990). Dominant grassland vegetation types include meadow steppe, typical steppe and desert steppe from east to west in Inner Mongolia (Wu, 1980). Primary production of grasslands in Inner Mongolia is extremely sensitive to inter-annual variation in climate and land-use change (Li, 1990; Xing & Liu, 1993; Xiao *et al.*, 1995a,c; Wang & Jiang, 1982; Zhang, 1990). Grasslands are vital resources for livestock and humans, and supported 67 million sheep units of livestock in 1985 (Li & Chen, 1987). CO_2-induced climate change and elevated atmospheric CO_2 concentration would have a significant impact on primary productivity of natural grasslands (Esser, 1992; Hall & Scurlock, 1991; Long & Hutchin 1991).

This study is part of a larger project investigating climate, soil texture and land-use controls of grassland ecosystem properties in Inner Mongolia from patch to region scales. We present here the preliminary results of sensitivity of dominant meadow steppe (*Filifolium sibiricum* steppe, *Stipa baicalensis* steppe and *Leymus chinense* steppe) and dominant typical steppe (*L. chinense* steppe and *S. grandis* steppe) at individual sites in Inner Mongolia to potential global climate change. In 8.6 million ha of meadow steppe, *F. sibiricum* steppe accounted for 1.86 million ha, *S. baicalensis* steppe for 1.66 million ha and *L. chinense* steppe for 1.47 million ha, while in 28 million ha of typical steppe, *S. grandis* steppe accounted for 2.68 million ha and *L. chinense* steppe for 4.49 million ha, respectively (Zhang, 1990).

These five vegetation types are dominated by C3 plants. The CENTURY model (Parton *et al.*, 1987, 1993) was employed to investigate the sensitivity of these grassland ecosystems to the following global change effects: (1)

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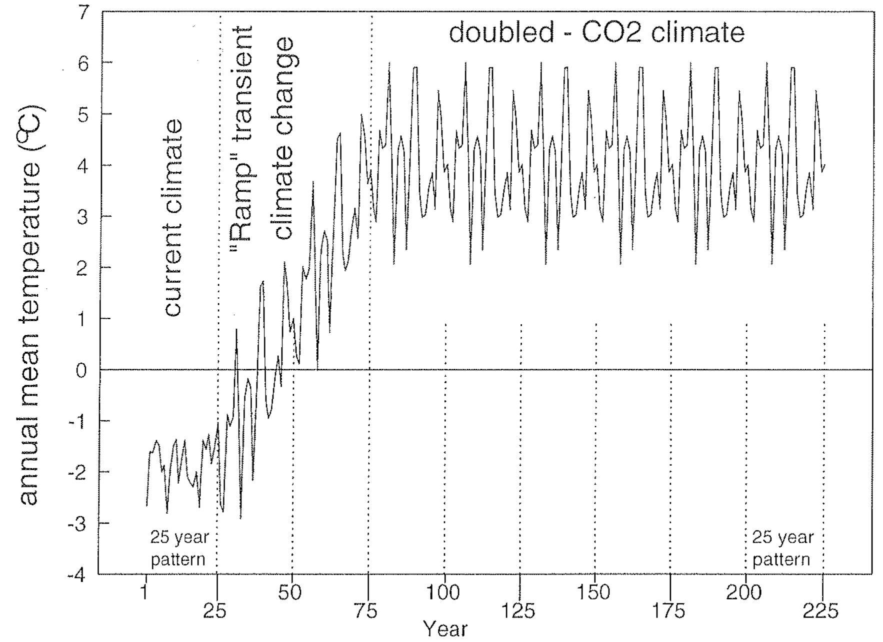

FIG. 1. Typical annual mean temperature climate file used in the CENTURY climate change runs. These files were generated based on current 25-year weather patterns which served as the template to implement the 50-year transient (ramp) and the modified doubled CO_2 climate for annual mean temperature and precipitation. A repeating 25-year pattern is used throughout the CENTURY simulations (this curve in the figure is the climate data for Tumugi).

climate change effect (i.e. change in monthly mean temperature and precipitation) and (2) combined effects of climate change and doubled atmospheric CO_2 concentration. Our objective is to quantify the impact of global climate change on net primary production and soil organic matter dynamics of these five dominant and high-quality grasslands in Inner Mongolia.

STUDY SITES AND METHODS

Study sites

The permanent fenced sites (25 ha each) of natural typical steppe (*L. chinense* steppe and *S. grandis* steppe) are located in the Xilin river basin (at 43°38′N and 116°42′E), Xilingol League, middle Inner Mongolia, which were established in 1979 for long-term ecological research by the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) of Chinese Academy of Sciences. The climate is continent middle temperate semi-arid. It is generally cold and dry in winter but warm and wet in summer. Annual mean temperature and annual precipitation in 1980–89 was about 0.02°C and 313.3 mm, respectively. The Xilin river basin (about 10,000 km^2 area) is dominated by *L. chinense* steppe and *S. grandis* steppe, both of which are representative of typical steppe in middle Inner Mongolia (Li, Yong & Liu, 1988). Dominant soils are chestnut and chernozem. Vegetation and ecosystems in the Xilin river basin are the most well preserved and in the main body of the Xilingol steppe reserve, designated as an UNESCO/MAB Biosphere reserve in 1988.

The fenced study sites of natural meadow steppe (*L. chinense* steppe, *S. baicalensis* steppe and *F. sibiricum* steppe) were established in 1981 at the Tumugi (46°10′N and 123°16′E), Xingan League, eastern Inner Mongolia for long-term monitoring of primary production of grasslands by the Tumugi Institute of Grasslands. The climate is middle temperate sub-humid. Annual mean temperature and annual precipitation in 1981–90 were 4.5°C and 411 mm, respectively. Dominant soils are chernozem and chestnut. Natural *L. chinense* steppe, *S. baicalensis* steppe and *F. sibiricum* steppe in the Tumugi area are representative of meadow steppe in eastern Inner Mongolia.

CENTURY model

The CENTURY model, a general model of plant–soil ecosystems, simulates the dynamics of C and N of various plant–soil systems (Parton *et al.*, 1987, 1988, 1992, 1993). It runs in a monthly time step and major input variables include monthly climate (minimum and maximum temperature, precipitation), plant chemistry characteristics (e.g. lignin content, plant N content) and soil properties (e.g. soil texture, soil depth, soil pH, bulk density, C and N levels). Many management measures (e.g. grazing, fire, cropping, fertilization, irrigation) have also been incorporated into the CENTURY model. The CENTURY model was already validated for the *L. chinense* steppe site and the *S. grandis* steppe site in IMGERS (Xiao *et al.*, 1995b) and for the *S. baicalensis* steppe site, the *F. sibiricium* steppe site and the *L. chinense* site in Tumugi (Xiao *et al.*, 1995c), using field data of soil organic matter and 10-year plant biomass.

Field and laboratory experiments show that elevated

TABLE 1. Projected difference in annual mean temperature ($D_{ann\text{-}t}$, °C), annual precipitation ($D_{ann\text{-}p}$, cm), average temperature ($D_{49\text{-}t}$, dgC) and total precipitation ($D_{49\text{-}p}$, cm) in April–September between $1{*}CO_2$ and $2{*}CO_2$ simulations.

		Temperature		Precipitation	
Site	GCM	$D_{ann\text{-}t}$	$D_{49\text{-}t}$	$D_{ann\text{-}p}$	$D_{49\text{-}p}$
IMGERS	CCC	6.3	6.7	1.5	2.6
	GFDL	4.9	5.0	−0.8	−1.3
Tumugi	CCC	5.9	5.7	0.6	0.82
	GFDL	5.3	5.9	−4.4	−4.4

atmospheric CO_2 concentration would increase photosynthesis, water use efficiency and nitrogen use efficiency (Owensby *et al.*, 1993a,b). In modelling the impact of doubling atmospheric CO_2 concentration (from 350 p.p.m. to 700 p.p.m.), a maximum of 20% increase in plant primary production was incorporated into the CENTURY model by modifying potential evapotranspiration (PET) and nutrient use efficiency (NUE), i.e. a 20% decrease of PET and a 20% increase in NUE (Ojima *et al.*, 1993a,b).

Climate data and model run

The doubled CO_2 climate data used to drive the CENTURY model in this study were derived by modifying the current monthly weather records for the past 25 years with the projected changes in monthly mean temperature and precipitation from two high-resolution general circulation models (GCMs) of Canadian Climate Center (CCC) and the Geophysical Fluid Dynamic Laboratory (GFDL) under $1{*}CO_2$ *v.* $2{*}CO_2$ scenarios. We assumed that these projected changes of temperature and precipitation would be reached within 50 years from the present, corresponding roughly to IPCC Scenario A (Houghton *et al.*, 1990). The 50-year ramp was generated by dividing the projected monthly climate change by 50 (Ojima *et al.*, 1993a) and then adding the resulting incremental change to each respective month within the 50-year ramp (Fig. 1). The projected change in monthly mean temperature was applied equally to monthly minimum and maximum temperature values.

The simulation in the 25-year period immediately following the 50-year ramp (i.e. 76th–100th year in Fig. 1) represented the transient response of these grassland ecosystems to global climate change. We conducted simulations with 150 years of stable modified weather data (i.e. 76th–225th years in Fig. 1) with the aim to determine a 'near-equilibrium' long-term response of grassland ecosystems. Average simulation results between the 25-year current climate period (i.e. the 1st–25th year in Fig. 1) and the last 25-year modified climate period (i.e. the 201st–225th year in Fig. 1) were compared to quantify changes in soil organic matter and plant production.

RESULTS

Magnitude of projected change in temperature and precipitation

In IMGERS, the projected changes in annual precipitation and annual mean temperature are lower than the projected changes of average temperature and total precipitation in April–September (Table 1). GFDL projects decrease of precipitation in May–July while CCC projects increase of precipitation in May–July (Fig. 2b). This distinct contrast in precipitation during May–July (i.e. seasonal distribution of precipitation) between CCC and GFDL may have a significant impact on plant primary production. The magnitude in projected change of temperature is much larger than the magnitude in projected change of precipitation for both CCC and GFDL (Fig. 2a,b).

In Tumugi, GCMs of both CCC and GFDL gave similar estimates in change of precipitation (Table 1). Projected large decreases of monthly precipitation in July and August (Fig. 3b) in GFDL may have a significant impact on plant biomass and primary production, as field data showed that precipitation in July and August are critical to plant biomass (Xiao *et al.*, 1995a).

Sensitivity of typical steppe *(L. chinense steppe and* S. grandis *steppe) in IMGERS*

Averaged over the 25-year period of current climate, simulated soil organic matter (SOM) and annual above-ground net primary production (ANPP) are 5809 $gC.m^{-2}$ and 97.8 $gC.m^{-2}$ for *L. chinense* steppe, and 5566 $gC.m^{-2}$ and 84.9 $gC.m^{-2}$ for *S. grandis* steppe, respectively. CENTURY simulations showed that global climate change resulted in considerable loss of soil organic matter and annual above-ground net primary production (Fig. 2c,d). Soil organic matter of the *L. chinense* site decreased by approximately 26% (1485 $gC.m^{-2}$) under CCC and 14% (828 $gC.m^{-2}$) under GFDL (Fig. 2c). Annual above-ground net primary production of the *L. chinense* site declined by 30% (29.5 $gC.m^{-2}$) under CCC and 28% (27.5 $gC.m^{-2}$) under GFDL (Fig. 2d). Soil organic matter of the *S. grandis* steppe site lost 25% (1411 $gC.m^{-2}$) under CCC and 10% (584 $gC.m^{-2}$) under GFDL (Fig. 2c). Annual above-ground net primary production of the *S. grandis* steppe site dropped by 29% (24.5 $gC.m^{-2}$) under CCC and 21% (18.3 $gC.m^{-2}$) under GFDL (Fig. 2d). These results indicated that *L. chinense* steppe is slightly more sensitive to climate change than *S. grandis* steppe. The large differences in projected loss of soil organic matter between CCC and GFDL for both *L. chinense* steppe and *S. grandis* steppe are clearly attributed to the difference in the magnitude and

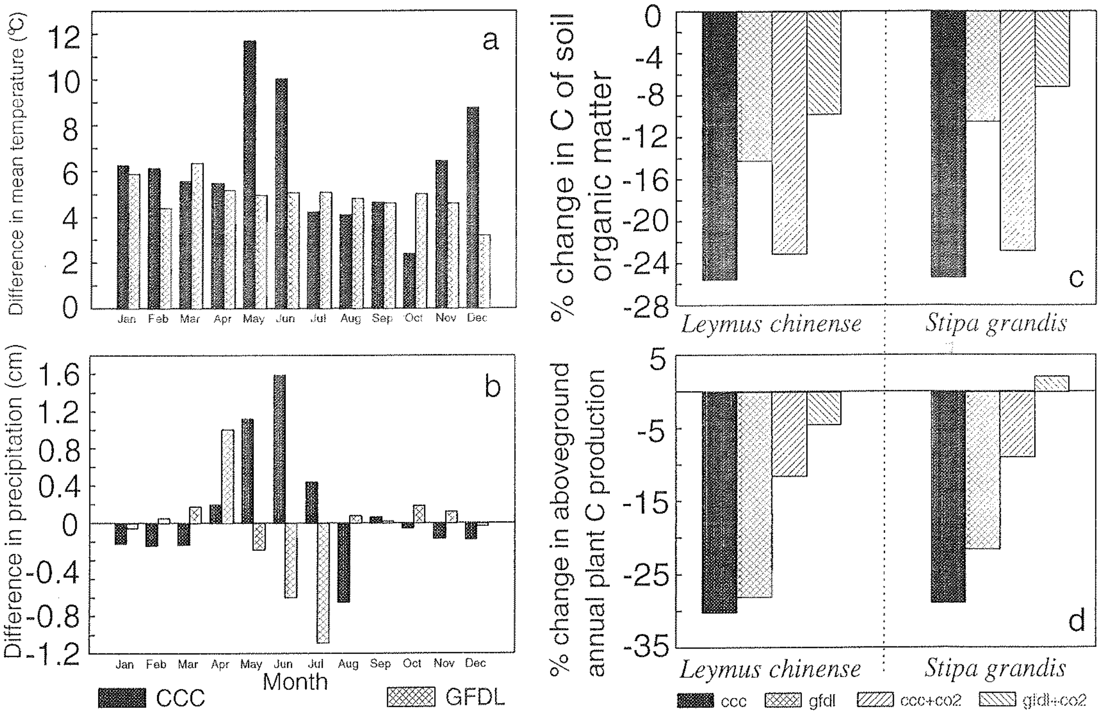

FIG. 2. Projected changes in temperature, precipitation, plant primary production and soil organic matter in IMGERS.

seasonal distribution of temperature projected by CCC and GFDL (Fig. 2b).

In the simulation of combined effects of CO_2 and climate change, soil organic matter decreased about 23% (1343 $gC.m^{-2}$) under CCC + CO_2 and 10% (570 $gC.m^{-2}$) under GFDL + CO_2 for *L. chinense* steppe, 22% (1270 $gC.m^{-2}$) under CCC + CO_2 and 7% (401 $gC.m^{-2}$) under GFDL + CO_2 for *S. grandis* steppe (Fig. 2c). ANPP of *L. chinense* steppe decreased by 12% (11.3 $gC.m^{-2}$) under CCC + CO_2 and 9% (4.4 $gC.m^{-2}$) under GFDL + CO_2 (Fig. 2d). ANPP of *S. grandis* steppe decreased by 5% (7.6 $gC.m^{-2}$) under CCC + CO_2 but increased by 2% (1.8 $gC.m^{-2}$) under GFDL + CO_2 (Fig. 2d).

Sensitivity of meadow steppe (*L. chinense* steppe, *F. sibiricum* steppe and *S. baicalensis* steppe) in Tumugi

Averaged over the 25-year period of current climate, the simulated soil organic matter and annual above-ground net primary production are 6061 $gC.m^{-2}$ and 89.4 $gC.m^{-2}$ for the *L. chinense* site, 5959 $gC.m^{-2}$ and 83.8 $gC.m^{-2}$ for the *F. sibiricum* site and 5988 $gC.m^{-2}$ and 85.7 $gC.m^{-2}$ for the *S. baicalensis* site, respectively. CENTURY simulations showed that these three sites have slight or even no difference in soil organic matter between CCC and GFDL (Fig. 3c). Soil organic matter decreases by approximately 13% (about 783 $gC.m^{-2}$) under CCC and 12% (about 734 $gC.m^{-2}$) under GFDL for the *L. chinense* steppe site, by 16% (926 $gC.m^{-2}$) under CCC and 20% (1164 $gC.m^{-2}$) under GFDL for the *F. sibiricum* steppe site, and by 14% (826 $gC.m^{-2}$) under CCC and 14% (854 $gC.m^{-2}$) under GFDL for *S baicalensis* steppe (Fig. 3c). However, there is a large difference in annual above-ground net primary production (ANPP) between CCC and GFDL (Fig. 3d). ANPP decreased by 22% (19.3 $gC.m^{-2}$) under CCC but 36% (32.1 $gC.m^{-2}$) under GFDL for *L. chinense* steppe, by 23% (17.6 $gC.m^{-2}$) under CCC but 37% (30.2 $gC.m^{-2}$) under GFDL for *F. sibiricum* steppe, and by 21% (19.2 $gC.m^{-2}$) under CCC but 35% (31.3 $gC.m^{-2}$) under GFDL for *S. baicalensis* steppe. This should be attributable to the large decreases of monthly precipitation in July (1.72 cm) and August (2.08 cm) in GFDL (Fig. 3b).

In the simulations of combined effects of CO_2 and climate change, loss of soil organic matter is slightly higher than the loss of soil organic matter in the simulation of climate change for *L. chinense* steppe, *S. baicalensis* steppe and *F. sibiricum* steppe, except for *F. sibiricum* steppe under GFDL + CO_2 (Fig. 3c). This indicated that CO_2 has no significant impact on soil organic matter dynamics which are largely determined by climate. However, CO_2 has significant impact on ANPP (Fig. 3d). ANPP decreased only by 7% (6.9 $gC.m^{-2}$) under CCC + CO_2 and 23% (20.6 $gC.m^{-2}$) under GFDL + CO_2 for *L. chinense* steppe, by 6% (5.3 $gC.m^{-2}$) under CCC + CO_2 and 21% (18.2 $gC.m^{-2}$) under GFDL + CO_2 for *F. sibiricum* steppe, and by 8% (7.3 $gC.m^{-2}$) under CCC + CO_2 and 24% (20 $gC.m^{-2}$) under GFDL + CO_2 for *S. baicalensis* steppe (Fig. 3d).

DISCUSSION

CENTURY simulations showed that typical steppe (*L. chinense* steppe and *S. grandis* steppe) in IMGERS and

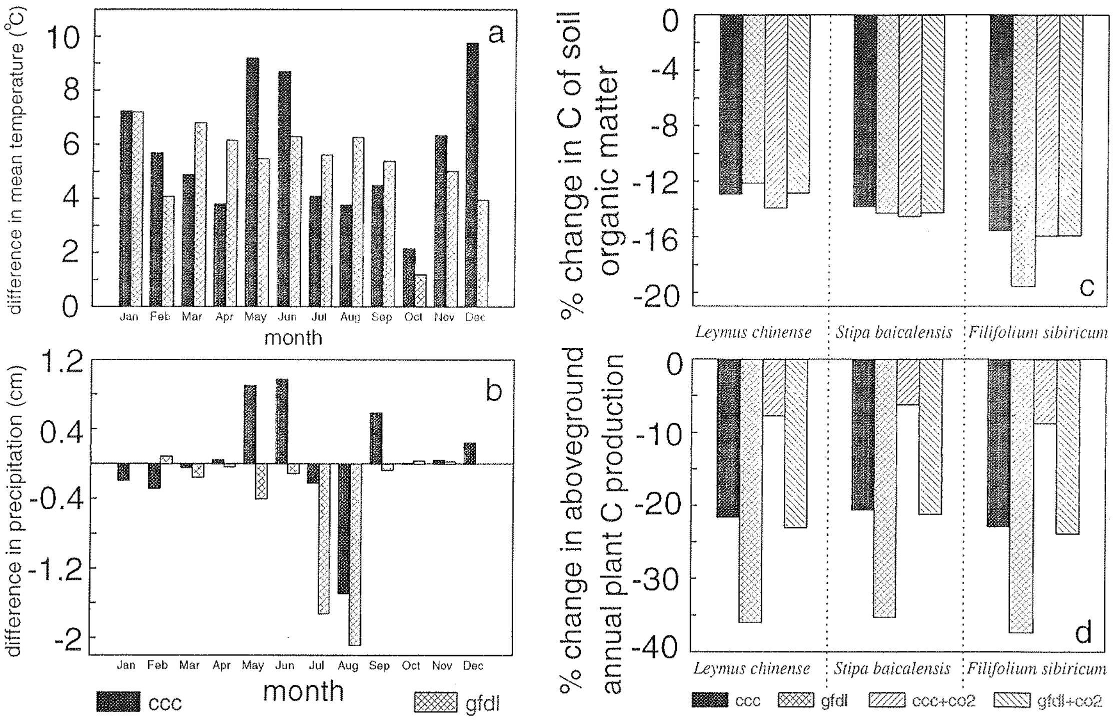

FIG. 3. Projected changes in temperature, precipitation, plant primary production and soil organic matter in Tumugi.

meadow steppe (*L. chinense* steppe, *S. baicalensis* steppe and *F. sibiricum* steppe) in Tumugi are very sensitive to climate change. In comparison of thirty-one grasslands throughout the world, Ojima *et al.* (1993a,b) found that the Eurasian grasslands lost the greatest amount of soil C (~ 1200 gC.m^{-2}) and soil C loss of other temperate grasslands ranged from 0 to 1000 gC.m^{-2}, averaging approximately 350 gC.m^{-2}. This large loss of soil C in Eurasian grasslands is clearly attributed to large increase of temperature projected by GCMs of CCC and GFDL, as decomposition of soil organic matter responds most predictably to change in temperature. Projected changes in annual mean temperature in IMGERS and Tumugi are about 6°C and are much larger than projected change in annual precipitation (less than 5% change). This may result in severe drought conditions in IMGERS and Tumugi areas, as potential evapotranspiration increases with temperature. Reconstruction of temperature and precipitation over the last 2000 years shows that in arid and semi-arid areas of China, precipitation increased while temperature increased, and vice versa (Gong & Hameed, 1993). Annual mean temperature and annual precipitation in the mid-Holocene in Inner Mongolia were about 2–3°C and 150–200 mm higher than current climate, respectively (Sun, 1992).

These five steppe ecosystems are also very sensitive to slight changes in seasonal distribution of precipitation and temperature, as projected by GCMs of CCC and GFDL. Both field observations and CENTURY simulations indicated that seasonal distribution of precipitation and temperature is an important control factor for plant primary production of typical steppe (*L. chinense* steppe and *S. grandis* steppe) in IMGERS (Xiao *et al.*, 1995a) and meadow steppe (*S. baicalensis* steppe, *F. sibiricum* steppe and *L. chinense* steppe) in Tumugi (Xiao *et al.*, 1995c) over time. The Intergovernmental Panel on Climate Change (IPCC) estimates (based on UKMO general circulation model climate projections) indicate that potential change in seasonal rainfall and temperature patterns in Central North America and the African Sahel will have a greater impact on biological response and feedback to climate than changes in the overall amount of annual rainfall (Houghton, Jenkins & Ephraums, 1990).

Climate change has a greater impact on primary production and soil organic matter dynamics of typical steppe (*L. chinense* steppe and *S. grandis* steppe) in IMGERS than those of meadow steppe (*L. chinense* steppe, *S. baicalensis* steppe and *F. sibiricum* steppe) in Tumugi. Among these five steppe vegetations, *S. grandis* steppe is the most drought-resistant steppe but provides the lowest quality of forage to livestock. Increase in ANPP of *S. grandis* steppe under GFDL + CO_2 may have a negative impact on the livestock industry in Inner Mongolia.

We have not taken vegetation change and redistribution under global climate change into consideration in this modelling study. Historical data showed that there were considerable shifts of vegetation distribution in Inner Mongolia (Sun, 1992). Land-use change is another important control of soil organic matter dynamics. Overgrazing by livestock results in a dramatic decrease of soil organic matter and primary production in Inner Mongolia. The area of degraded grasslands and desertification in Inner Mongolia accounted for more than 30% of its total grasslands, due to livestock overgrazing and irrational crop cultivation (Zhang, 1990). In the Central Great Plains grasslands of the United States, the simulated losses of soil organic C from global climate change over a 50-year period are relatively small compared with calculated losses from cultivation over a comparable period (Burke *et al.*, 1991). Further study on the combined impact of land-use change and climate change on Inner Mongolia grasslands are critically needed.

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