Climatic Change (2013) 117:259–272
DOI 10.1007/s10584-012-0533-2

Sensitivity of carbon budget to historical climate variability and atmospheric CO_2 concentration in temperate grassland ecosystems in China

Xinghua Sui · Guangsheng Zhou · Qianlai Zhuang

Received: 29 August 2010 / Accepted: 26 June 2012 / Published online: 10 July 2012

Abstract Chinese temperate grasslands play an important role in the terrestrial carbon cycle. Based on the parameterization and validation of Terrestrial Ecosystem Model (TEM, Version 5.0), we analyzed the carbon budgets of Chinese temperate grasslands and their responses to historical atmospheric CO_2 concentration and climate variability during 1951–2007. The results indicated that Chinese temperate grassland acted as a slight carbon sink with annual mean value of 7.3 Tg C, ranging from -80.5 to 79.6 Tg C yr^{-1}. Our sensitivity experiments further revealed that precipitation variability was the primary factor for decreasing carbon storage. CO_2 fertilization may increase the carbon storage (1.4 %) but cannot offset the proportion caused by climate variability (-15.3 %). Impacts of CO_2 concentration, temperature and precipitation variability on Chinese temperate grassland cannot be simply explained by the sum of the individual effects. Interactions among them increased total carbon storage of 56.6 Tg C which 14.2 Tg C was stored in vegetation and 42.4 Tg C was stored in soil. Besides, different grassland types had different responses to climate change and CO_2 concentration. NPP and R_H of the desert and forest steppes were more sensitive to precipitation variability than temperature variability while the typical steppe responded to temperature variability more sensitively than the desert and forest steppes.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-012-0533-2) contains supplementary material, which is available to authorized users.

X. Sui · G. Zhou (✉)
State Key Laboratory of Vegetation and Environmental Change, Institute of Botany,
Chinese Academy of Sciences, Beijing 100093, China
e-mail: gszhou@ibcas.ac.cn

G. Zhou
Chinese Academy of Meteorological Sciences, Beijing 100081, China

Q. Zhuang
Department of Earth and Atmospheric Sciences and Department of Agronomy, Purdue University,
West Lafayette, IN 47906, USA

X. Sui
Graduate School of Chinese Academy of Sciences, Beijing 100049, China

1 Introduction

Terrestrial carbon budget globally provides a sink for about 25 % of anthropogenic carbon emissions that increase atmospheric CO_2 concentration and a positive feedback in a warming world, albeit of uncertain magnitude (Dorothy 2000; Houghton 2007; Running 2008). Global vegetation carbon storage estimates suggested that grasslands probably contribute over 10 % of the total biosphere carbon storage (Nosberger et al. 2000). Moreover, the carbon storage density of temperate grassland is two to four times of tropical grassland (Houghton and Hackler 1995). Thus, temperate grassland ecosystems are of particular importance to the global carbon budget.

Temperate grasslands in China are the third largest grassland area in the world (Lee et al. 2002), constituting an integral part of the Eurasian grassland ecosystem to the east of the continent and mainly distributed along the northernmost boundary of China summer monsoon (Qian et al. 2007). These ecosystems are more xeric and water stressed than many other ecosystems (Li et al. 2005; Niu et al. 2008) and are predicted to see some of the strongest and earliest effects of climate change (IPCC 2007) as a gradually warmer and drier climate has already documented in this area (Lu et al. 2009). Lots of mechanism studies on response, adaption and feedback of grassland ecosystem to global change have been carried out (Bai et al. 2010a, b) to address the potential effects of CO_2, temperature, precipitation, nitrogen (N) deposition and their interactions. Field manipulative experiment results suggested both water and N are important limiting resources in this area (Liu et al. 2009; Xia et al. 2009) and indicated the dependence of N effects on variations in hydrological condition (Niu et al. 2008). Besides the model efforts aiming at evaluating net primary productivity in temperate grassland to atmospheric CO_2 and associated climate change (Xiao et al. 1995; Ni 2001, 2004; Piao et al. 2009), field programs such as eddy-covariance observation methods have been used to provide full daily and seasonal budgets of net grassland ecosystem carbon flux (Kato et al. 2004; Hao et al. 2006; Fu et al. 2006). However, large uncertainty remained in estimating annual carbon budget of grassland ecosystems (Baldocchi et al. 2004). This uncertainty is primarily attributed to the sensitivity of grasslands to inter-annual variability in climate, biomass dynamics (Meyers 2001; Flanagan et al. 2002; Niu et al. 2009a, b) and incomplete understanding of the responses of grassland ecosystem processes at regional scale to changing climate and atmospheric composition (Wever et al. 2002). As observed nitrogen deposition rate was relative low (about 1~2 gN m^{-2}) (Tian et al. 2011) in the arid to semiarid regions with less industrial or agricultural sources, Lu et al. (2012) reported that Chinese grassland sequestered less than 10 gC m^{-2} yr^{-1} in response to deposited nitrogen enrichment limited by low temperature and/or low soil moisture. Previous study on ozone effect (Ren et al. 2007) also indicated that inter-annual variation in net carbon flux was primarily controlled by climate variability in the study area.

Thus, the primary objective of this paper is to investigate the carbon dynamics of Chinese temperate grasslands and their responses to historical climate variability and atmospheric CO_2 during 1951–2007, while ignoring other major disturbances such as land use change resulting from human activities (Houghton and Hackler 2003; Liu et al. 2005; Liu and Tian 2010), ozone pollution (Felzer et al. 2005) and nitrogen deposition. To achieve this goal, a process-based biogeochemical model Terrestrial Ecosystem Model (TEM; Zhuang et al. 2003) was applied. First, the model parameterizations were calibrated using the information available from intensively studied field sites to estimate initial values of each of the rate-controlling parameters among the carbon and nitrogen pools. We then evaluated the TEM simulated carbon budgets with eddy-covariance observation data (NEP) as well as net primary productivity (NPP), vegetation and soil organic carbon from multi-sites biomass and soil profile data. Finally, we conducted a group of sensitivity experiments to evaluate the responses of the carbon budget to different scenarios and their controlling climatic factors.

2 Data and methods

2.1 Data

Temperate grasslands in China cover 64.9 Mha and are dominated by three major types: forest steppe, typical steppe and desert steppe. They are distributed (35°–51°N, 83°–127°E) from Songliao Plain adjacent to Inner Mongolia plateau to Loess Plateau and partly in Altai Mountains which all belong to the Eurasian continent grassland region (Fig. 1). The study area is located in the temperate semi-arid and semi-humid zone, with annual average temperature varying from -3 to -9 °C and annual average precipitation from 150 to 600 mm.

Meteorological data used in this study including temperature, solar radiation and precipitation were collected from 752 national standard weather stations from National Meteorological Information Center of China Meteorological Administration(CMA). This dataset was used to generate daily meteorological dataset with the spatial resolution of 10 km × 10 km by the DAYMET algorithm (Thornton et al. 1997; Thornton and Running 1999) and then summed up for monthly dataset as model input. Soil data was acquired from the database of Nanjing Institute of Soil, the Chinese Academy of Sciences, originally derived from the soil elemental dataset based on over 5000 soil profile data throughout the country. Vegetation data including vegetation type and corresponding fractional area was derived from "Vegetation Regionalization Map of China" (1:1000,000) (Zhang 2007) and "1:100 million China grassland resources map" from Institute of Geographical Sciences and Natural Resources, the Chinese Academy of Sciences. Annual atmospheric CO_2 data were obtained from ESRL data (www.esrl.noaa.gov/gmd/ccgg/trends/).

Fig. 1 Study area of temperate grasslands in China derived from "Vegetation Regionalization Map of China" (1:1 million) compiled by the Editorial Board of Vegetation Map of China (Zhang 2007)

Four field sites with eddy-covariance observations (Table S3) were organized to validate TEM simulated NEP including Xilinhot (2004 to 2006) (Wang et al. 2008), Dongsu (2008 to 2009) (Yang et al. 2011), Tongyu (growing season from 2008 to 2009) and Yuzhong (growing season from 2008 to 2009) (Sui and Zhou 2012). To further validate TEM at regional scale, we collected biomass data and soil organic carbon data within the study area from published literatures (Yang et al. 2010a, b). Repeated samples in the same grid cell were averaged. Grazing sites were also excluded since we have not considered land use/land cover change in our current study.

2.2 Terrestrial ecosystem model (TEM)

The Terrestrial Ecosystem Model (TEM, Figure S1) is a process-based, global-scale ecosystem model that uses spatially referenced information on climate, elevation, soils, and vegetation to make monthly estimates of carbon and nitrogen fluxes and pool sizes of the terrestrial biosphere (see Supplementary material for details). In this study, the TEM was coupled with a soil thermal model based on the Goodrich model (Goodrich 1976) to account for the effects of soil temperature on ecosystem processes (Zhuang et al. 2001, 2003).

To apply the TEM at Chinese temperate grasslands, model calibration is necessary based on the observed data including annual ecosystem carbon and nitrogen fluxes and pools (Table S1). During the calibration, TEM was run continuously with long-term average climate data and an atmospheric CO_2 concentration of 340 ppmv. The parameter values were changed until the simulated fluxes and pool sizes matched the field data with a certain tolerance (e.g., 1 %), and the obtained parameter values were then considered as optimal for the site. Three criteria were used in sequence to judge the success of calibration: (1) the modeled annual NPP and GPP matched the observations; (2) annual nitrogen uptake wass close to the observations; and (3) annual NEP converged to nearly zero with the prescribed tolerance (1 %). These three criteria can make sure the model parameters which are closely correlated with carbon allocation will be well constrained by observation data (see Zhuang et al. 2001 for details).

2.3 Regional simulation and sensitivity experiments design

Five experiments (Table 1) and one baseline experiment were designed to examine the sensitivity of carbon flux and carbon storages in Chinese temperate grasslands to historical atmospheric CO_2 concentration, air temperature and precipitation during the study period.

For all these regional simulations, we first ran TEM continuously with long-term average climate data and CO_2 concentration from 1951 to 2007 in each grid cell, and then spun up the model for 45 years with the meteorological data from 1951 to 1996 to account for the

Table 1 Sensitivity experiments design

Experiment	CO_2 concentration	Temperature	Precipitation
baseline	311.41ppmv (value of 1951)	Mean value from 1951 to 2007	Mean value from 1951 to 2007
1	Historical data	Mean value from 1951 to 2007	Mean value from 1951 to 2007
2	311.41ppmv (value of 1951)	Historical data	Mean value from 1951 to 2007
3	311.41ppmv (value of 1951)	Mean value from 1951 to 2007	Historical data
4	311.41ppmv (value of 1951)	Historical data	Historical data
5	Historical data	Historical data	Historical data

influence of inter-annual climate variability on the initial condition of undisturbed ecosystem. Finally, we ran the model with transient monthly climate data.

3 Results

3.1 Model validation

The parameterized TEM was verified by the NPP data collected in our previous study (Sui and Zhou 2012) (Table S2). The parameterized TEM well simulated NPP in comparison with observations (R^2=0.57, p<0.01, N=28) (Figure S2), performing better for the forest steppe (R^2=0.67, p<0.01, N=8), the typical steppe (R^2=0.67, p<0.01, N=12) and the desert steppe (R^2=0.58, p<0.05, N=5), respectively.

The parameterized TEM is also able to reproduce the temporal trends of net ecosystem production (NEP) at Xilinhot site and Dongsu site (Figure S3a,b) (R^2=0.31, p<0.01, N=36; R^2=0.48, p<0.01, N=24). TEM simulated NEP also well matched EC observed NEP at Tongyu site and Yuzhong site during growing seasons (Figure S3c,d) (R^2=0.50, p<0.05, N=7; R^2=0.57, p<0.05, N=6).

Soil organic carbon (SOC) storage is determined by the long-term net balance of photosynthesis and total respiration in terrestrial ecosystems. We compared our averaged vegetation biomass (VEGC) and SOC estimates during 2001–2005 with non-grazing sites in this region (Yang et al. 2010a, b) (Figure S4a, S4b). TEM simulated SOC and VEGC were comparable to observed values but tended to underestimate VEGC at some forest steppe sites. The discrepancy between simulations and our observations may be due to the underestimates of these pools in our parameterization sites, leading to lower values in these verification sites.

3.2 Climate and carbon budget dynamics

There was a significant increasing trend of annual mean temperature (Fig. 2a) (R^2=0.66, p< 0.01, N=57) at the rate of 0.04 °C yr^{-1} ranging from 2 °C to 6 °C. Annual precipitation did show a significantly decreasing trend (Fig. 2b) (R^2=0.00, p>0.05, N=57) ranging from 263 to 500 mm. As a consequence of increasing soil temperature (R^2=0.70; p<0.01, N=57) (Fig. 2c) and precipitation showing no significant changes, the regional soil moisture showed a drying trend since mid 1980's (Fig. 2b, d). Spatially, the drying trend evidently appeared in the north east part with volumetric soil moisture decreased from 40–50 % in the 1970s to a level of 20–30 % in the 2000s (data not shown).

During the past 57 years, the temperate grasslands exhibited significant inter-annual variability of carbon dynamics (Fig. 2e–g). Annual mean NEP of temperate grassland was a weak carbon sink of 11.25 gC m^{-2} with high inter-annual variability from -124 to 122.7 gC m^{-2}. Temporal variation of annual NEP was significantly correlated with precipitation (R^2= 0.26, p<0.01, N=57), while not significantly correlated with annual mean temperature (R^2= 0.001, p>0.05, N=57). Consequently, the regional vegetation and soil carbon increased (Fig. 2h, i). During the study period, TEM estimates of the regional vegetation and soil carbon were 0.58 and 2.81 P g C. Overall, the regional sink slightly increased due to warming climate and rising CO_2 concentration.

NEP of three temperate grassland types showed similar inter-annual fluctuation with different magnitudes and patterns. Desert steppe showed lowest carbon sink capacity (6.98 gC m^{-2}) and highest standard deviation (108.5 gC m^{-2}). Typical and

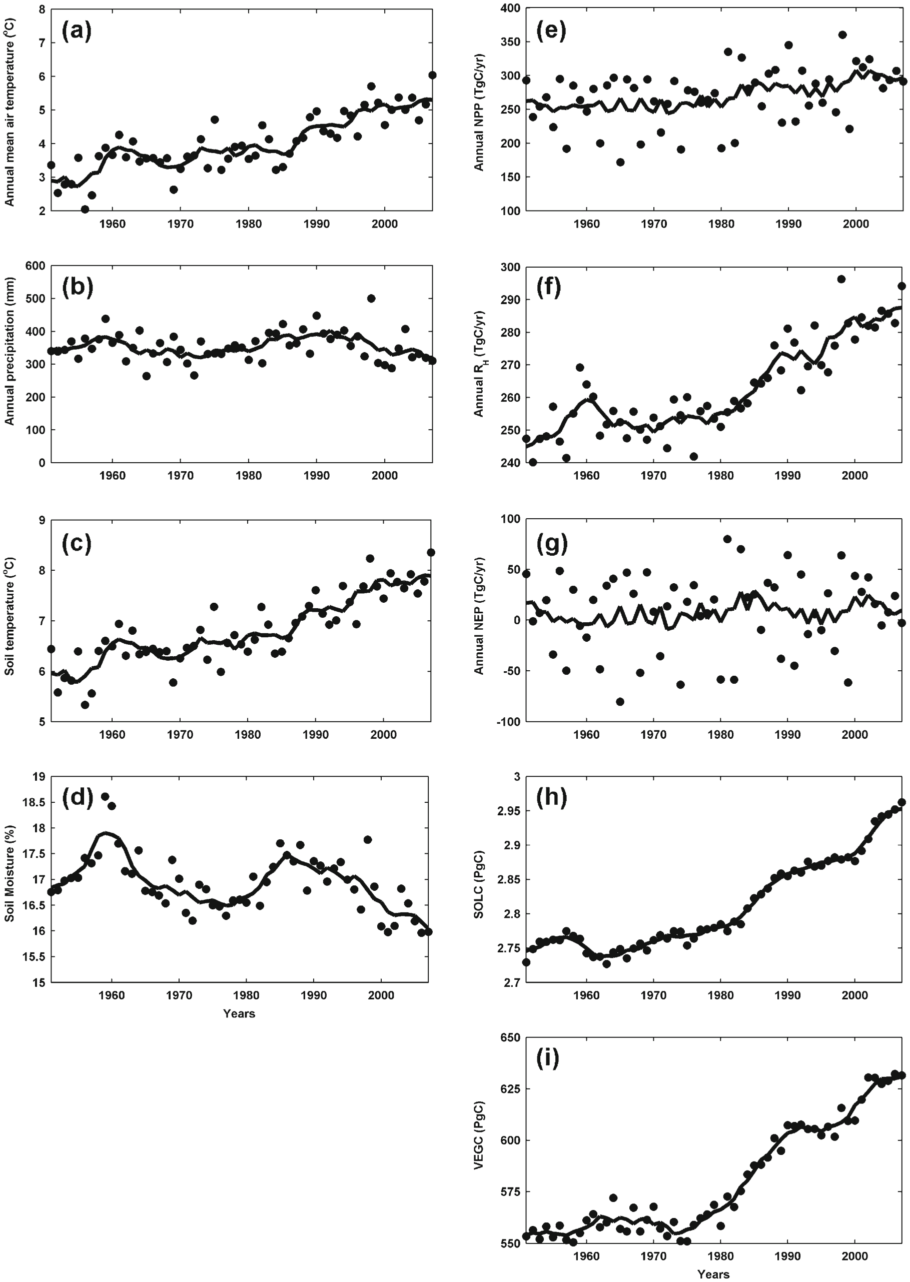

Fig. 2 Interannual variations of annual mean air temperature (**a**), annual precipitation (**b**),soil temperature (**c**), soil moisture (**d**), net primary production (NPP)(**e**), heterotrophic respiration (R_H)(**f**), net ecosystem production (NEP) (**g**), soil organic carbon (**h**) and vegetation carbon (**i**) in the temperate grassland of China from 1951 to 2007. The dark thicker lines are 5-year running averages to show the trends

forest steppes showed greater variation (-33.4 - 33.1 and -25 - 22 Tg C yr^{-1}) mainly due to their larger distribution areas. Our simulations also indicated that there was great spatial variability in the strength of the sink or source in the region (Fig. 3g–i). During the 1960s, 1980s and 2000s, the study region experienced continuous warming (Fig. 3a–c) and dry-wet-dry precipitation regime shift (Fig. 3d–f). Regional sink became stronger mainly due to an increasing sink especially in typical steppe areas. In general, the northeastern region of forest steppe acted as a carbon source while the southwestern region gradually became a carbon sink. There was also a general trend of carbon source to sink moving from north to south across the region.

3.3 Sensitivity of carbon budget

3.3.1 Baseline

The baseline run was conducted with the CO_2 concentration of 311ppmv and mean monthly climate data during the study period. Each grid cell in the baseline simulation was determined to reach equilibrium when the annual fluxes of NPP and heterotrophic respiration (R_H) differ by less than 0.1 gC m^{-2} yr^{-1}. Although CO_2 concentration was low in this simulation, temperate grasslands showed greater carbon sequestration capacity under mean monthly climate situation. Simulated grassland carbon and soil organic carbon stocks in this run were 640 Tg C and 3005 Tg C, respectively (Table 2).

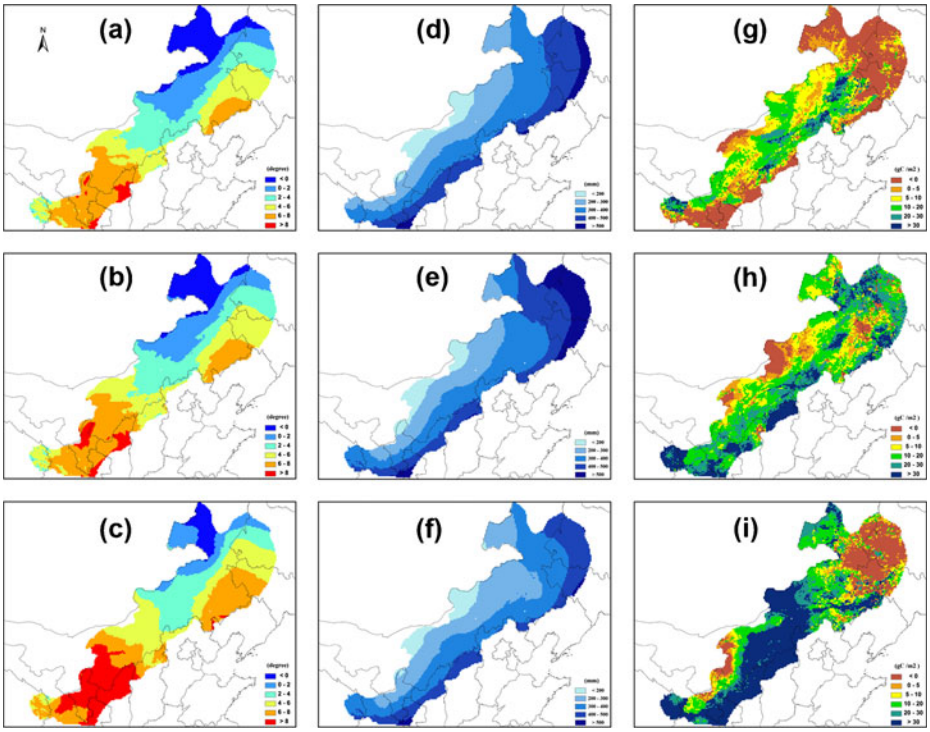

Fig. 3 Spatial distribution of decadal mean air temperature in the 1960s(**a**), 1980s(**b**), 2000s(**c**); decadal annual precipitation in the 1960s(**d**), 1980s(**e**), 2000s(**f**); decadal annual mean NEP in the 1960s(**g**), 1980s(**h**), 2000s

Table 2 Responses of vegetation carbon, reactive soil organic carbon and total carbon storage to changes in atmospheric CO_2 concentration and climate variability during 1951–2007

	Vegetation C			Reactive soil organic C			Total C		
	/10^{12}gC			/10^{12}gC			/10^{12}gC		
Baseline	640			3005			3645		
	Increase of carbon /10^{12}gC	Increase rate compared to the baseline /%	Linear fit of carbon increase /10^{12}gC yr^{-1}	Increase of carbon /10^{12}gC	Increase rate compared to the baseline /%	Linear fit of carbon increase /10^{12}gC yr^{-1}	Increase of carbon /10^{12}gC	Increase rate compared to the baseline /%	Linear fit of carbon increase /10^{12}gC yr^{-1}
1	6.85	1.07 %	0.63	43.3	1.44 %	2.37	50.15	1.38 %	3
2	-4.94	-0.77 %	1.19	-2.32	-0.08 %	-1.14	-7.26	-0.20 %	0.05
3	-44.83	-7.00 %	1.73	-252.82	-8.41 %	2.63	-297.65	-8.17 %	4.36
4	-43.7	-6.82 %	2.33	-237.36	-7.90 %	1.37	-281.06	-7.71 %	3.7
5	-60.42	-9.44 %	3.11	-194.55	-6.47 %	3.72	-254.97	-7.00 %	6.83
6*	-17.5	-2.73 %		17.29	0.58 %		-0.21	-0.01 %	

*Stands for 5-(1+2+3) indicating the interactions among CO_2, temperature and precipitation

3.3.2 CO_2 concentration

Vegetation and soil organic carbon stocks increased 1.38 % in response to atmospheric CO_2 concentration alone (Table 2, Fig. 4a). Annual NPP of grassland increased by 0.2 Tg C yr^{-1} higher than R_H (0.1 Tg C yr^{-1}), inducing an increasing trend of NEP. Annual mean NEP was 2.91 Tg C, varying from 0.14 to 5.38 Tg C. Although different grasslands have different responses to CO_2 elevation, all the grassland types tended to show increasing ability of carbon acquisition. With the best hydrothermal conditions, forest steppe had the highest carbon sink capacity. Strangely, typical steppe showed the lowest carbon sink capacity other than desert steppe. This result implies that the responses of grasslands production to increasing CO_2 may be substantially limited by nitrogen availability as well as water availability.

3.3.3 Temperature variability

From 1951 to 2007, a significant warming trend increased both NPP and R_H in temperate grasslands (Fig. 4b). Annual mean NEP was 0.3 Tg C, ranging from -11.16 to 13.4 Tg C. Temperature variability obviously affected soil temperature (TSOIL) ($R^2=0.806$, $p<0.01$, $N=57$), significantly promoted the processes of evapotranspiration (EET) and net nitrogen mineralization (NMIN) ($R^2=0.34$, $p<0.01$, $N=57$; $R^2=0.239$, $p<0.01$, $N=57$), and reduced volumetric soil moisture (VSM) ($R^2=0.297$, $p<0.01$, $N=57$). Both NPP and R_H of all three types were sensitive to soil temperature. Although different grasslands responded at different extents to temporal and spatial variations of temperature (see supplementary materials for details, Table S4), all grassland types tended to show no significant trends of NEP due to close increment rates between NPP and R_H (Table S5).

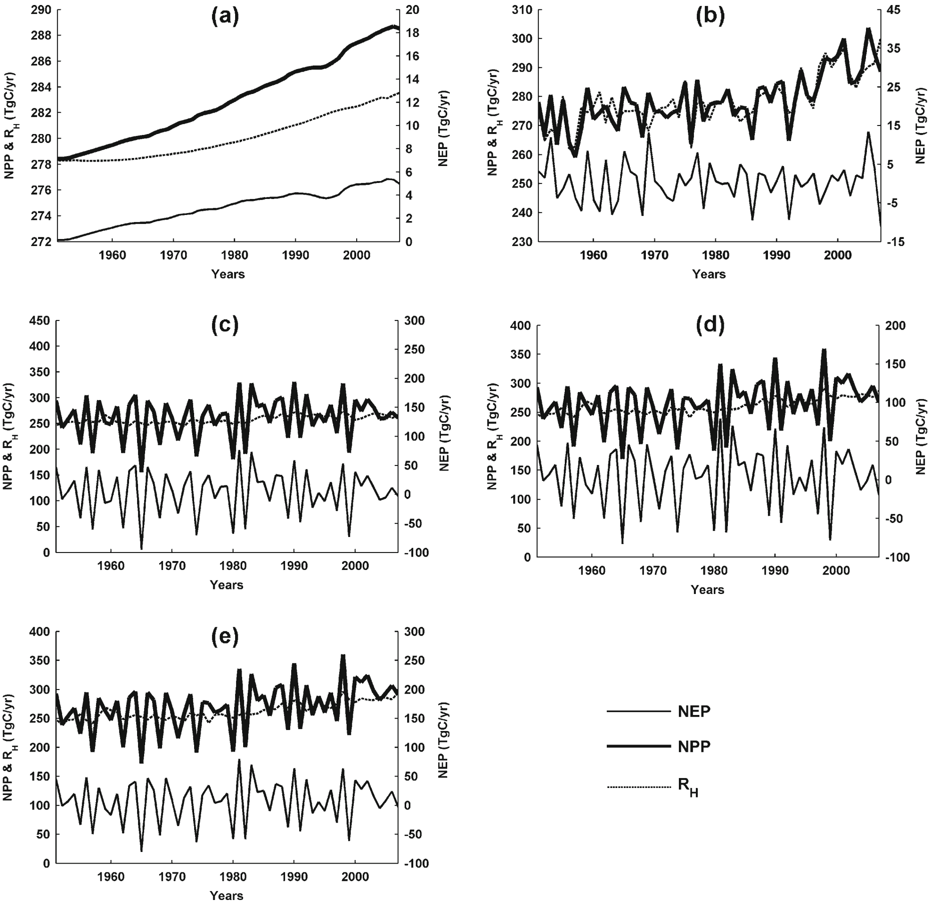

Fig. 4 Inter-annual variation in NEP, NPP and R_H in temperate grassland of China induced by historical CO_2 concentrations alone (**a**), historical temperature alone (**b**), historical precipitation alone (**c**), historical temperature and precipitation (**d**) and historical CO_2 concentration, temperature and precipitation (**e**) from 1951–2007

3.3.4 Precipitation variability

The variability of precipitation has induced a substantial change to NEP in the temperate grasslands of China (Fig. 4c). NPP was clearly more sensitive to the changes of precipitation than R_H. In most years, increasing precipitation would increase NPP, making the whole region act as a carbon sink of atmospheric CO_2. Annual mean NEP was 4.32 Tg C ranging from -95 to 77 Tg C, three to fourfold of the magnitude in the context of temperature variability alone. Precipitation variability directly affected soil moisture ($R^2=0.783, p<0.01$, $N=57$). Increasing precipitation significantly increased evapotranspiration ($R^2=0.72$, $p<0.01$, $N=57$), reduced net nitrogen mineralization ($R^2=0.195$, $p<0.01$, $N=57$), but induced no significant effect on soil temperature ($R^2=0.079$, $p>0.05$, $N=57$). Different grasslands responded at different extents to precipitation variability (see supplementary materials for details, Table S4), but all grasslands tended to show increasing ability of carbon acquisition due to overwhelming increment of NPP than R_H.

3.3.5 Climate variability

In the context of both temperature and precipitation variability but fixed CO_2 concentration, NPP in temperate grasslands showed higher sensitivity to precipitation than to temperature. Inter-annual variations of NPP and NEP were similar to the case of precipitation variability alone (Fig. 4d). Annual mean NEP was 3.95 Tg C, ranging from -82.6 to 79.6 Tg C. Climate variability directly affected soil temperature (R^2=0.808, p<0.01, N=57). Increasing temperature significantly reduced evapotranspiration (R^2=0.739, p<0.01, N=57) and soil moisture (R^2=0.779, p<0.01, N=57), but induced no significant effect on net N mineralization (R^2= 0.20, p<0.01, N=57).

Although response of three grassland types were similar to the case of precipitation variability alone, interaction of precipitation and temperature reduced the coefficient of determination between NPP, R_H and the evapotranspiration, net mineralization, soil volumetric moisture, soil temperature(supplementary materials for details, Table S4). NPP of all grasslands tended to increase with more precipitation and rising temperature, but the same response of R_H to climate variability offsets the enhancement. As result, climate variability tended to reduce the carbon sink ability (Table S5).

3.3.6 Climate variability and CO_2 concentration

On average, the temperate grasslands acted as a carbon sink of 7.3 Tg C yr^{-1} ranging from 79.6 to -80.5 Tg C yr^{-1} (Fig. 4e). Inter-annual change of NPP was quite similar to the case of precipitation variability alone (Fig. 4d). In contrast, R_H changed at a larger magnitude (240–296 Tg C) than in the case of temperature variability alone (261–300 Tg C) or the case of precipitation variability alone (244–274 Tg C), but similar to the magnitude in the case of precipitation and temperature variability (240–291 Tg C). This may induce that inter-annual change of NPP can be mainly interpreted by precipitation variability while inter-annual change of R_H should be interpreted by the combination of precipitation and temperature variability. Furthermore, different grasslands responded at different extents to the combination of elevated CO_2 concentration, precipitation and temperature variability (supplementary materials for details, Table S4). NPP of the temperate grasslands tended to increase with elevated CO_2, increasing precipitation and higher temperature. Meanwhile, R_H tended to respond to climate change in the same direction.

4 Discussion and conclusions

This study represented an attempt to explicitly examine the regional carbon dynamic and its response to climate change on the temperate grasslands of China. Temperate grassland ecosystems were reported to be a small sink to neutral with highly intra and inter-annual variations by short-term eddy flux observation studies (e.g., Wang et al. 2008; Hao et al. 2006) and factorial experiments (Niu et al. 2008). However, this carbon sink may switch to a carbon source under drought stress as observed at Mongolian steppe grassland (Li et al. 2005) and Inner Mongolian typical steppe grassland (Hao et al. 2006). These analyses were consistent with other studies suggesting that volumetric water content influences the process of net nitrogen mineralization thus indirectly affects NPP (Yuan et al. 2006). The increase in nitrogen availability affected the carbon budget of the grasslands indicated by Xia et al. (2009). Together with increasing R_H when air temperature increased, the lower NPP resulted in a carbon source, which was consistent to Fu et al. (2006).

TEM estimate of vegetation carbon in the study area (64Mha) was 580 Tg C, comparable to Fan et al. (2008)'s estimate of 520 Tg C (75Mha). Grassland carbon densities of typical and desert steppes were 485 gC m^{-2} and 204 gC m^{-2}, comparable to Ma et al. (2010)'s estimates of 343 gC m^{-2} and 211.4 gC m^{-2}, respectively. However, TEM estimated vegetation carbon of 444 Tg C (24Mha) in forest steppe was much higher than Ma et al. (2006)'s estimate of 97.4 Tg C (17.5Mha) over the meadow steppe and meadow in Inner Mongolia. This overestimate was partially due to parameterization with higher values of observational data (Table S1.1).

TEM estimate of soil organic carbon stock in temperate grasslands was 2810 Tg C from 1951 to 2007. Carbon density was 4.5 kg C m^{-2} in typical steppe, 5.4 kg C m^{-2} in forest steppe and 1.8 kg C m^{-2} in desert steppe. These results were within the range of Wang et al. (2003)'s estimates (4.5 kg C m^{-2}, 3.8 to 5.8 kg C m^{-2} and 2.1 to 2.4 kg C m^{-2}), but much lower than Yang et al. (2010b)'s field measurements (6.36 kg C m^{-2}, 12.69 kg C m^{-2} and 3.74 kg C m^{-2}). The discrepancy between our observations and field measurements may be partly due to the different sampling depths of soil profiles as well as different vegetation classification systems.

Our sensitivity experiments indicated that precipitation variability was the primary factor for decreasing carbon storage (Table 2). CO_2 fertilization may increase the carbon storage (1.44 %) but cannot offset the proportion caused by climate variability. Impacts of CO_2 concentration, temperature and precipitation variability on Chinese temperate grassland cannot be explained by simply summed up their individual effect. Temperate grasslands tended to be a carbon sink of 2.91, 0.3, 4.32, 3.95, 7.3 Tg C yr^{-1} in all the five sensitivity experiments, respectively.

Sensitivity experiment results also suggested that NPP and R_H of the temperate grasslands were significantly affected by both temperature and precipitation variability, not sensitive to CO_2 concentration. NEP showed no significant change due to the imbalance variability between NPP and R_H. NPP and R_H of desert and forest steppes were more sensitive to precipitation variability than temperature variability, while R_H of forest steppe was more sensitive to CO_2 concentration than desert steppe. NPP and R_H of typical steppe responded to temperature variability more sensitively than those of desert and forest steppes. Furthermore, NPP of typical steppe was most sensitive to elevated CO_2 concentration.

It should be addressed that our study did not take land use/land cover change into consideration, which brought out certain uncertainty to the results and underestimated the possible carbon emission due to land use/land cover change. While the study of grasslands cover change have reached out some results (Liu and Tian 2010; Houghton and Hackler 2003), our understanding of potential effects of land use change such as grazing and fencing on grassland carbon dynamics is still limited by available data and experimental proof. Meta-analysis suggested that grazing can lead to a large amount of C loss from soils, while other factors such as fencing can result in an increase in soil C stock (Shi et al. 2009). However, a few studies indicated that C sequestration increased with moderate grazing (Wang et al. 1998; Wang et al. 2011) and compensatory growth responses to grazing intensity among years may mainly due to temporal variability in precipitation (Schönbach et al. 2011). Additional experiments will have to be designed to testify the contradicting results. Furthermore, techniques to quantify and describe grazing activity at regional scale should also be developed which limit our ability to model its effect on grassland carbon budget. In addition, climate change of the last 57 years is characterized by evident increasing temperature, which will cause structural and functional changes of ecosystems as well as their spatial distributions. Although historical nitrogen deposition rate was low in this area, the increasing trend may also induce changes in grassland community structure and ecosystem functioning in the future (Bai et al. 2010b). Meanwhile, adaptation and evolution of ecosystems to are a slow process which will also alter the carbon exchange and carbon storage of terrestrial ecosystems. Our model still lacks such ability to describe the processes. Uncertainty and equifinality accompanied with the parameterization of soil carbon and nitrogen cycles should not be overlooked to evaluate the accuracy of the results.

Acknowledgements This research was jointly supported by State Key Development Program of Basic Research (2010CB951303), Strategic Priority Research Program - Climate Change: Carbon Budget and Related Issues of the Chinese Academy of Sciences (XDA05050408) and China National Natural Science Foundation (No. 90711001).

References

Bai W, Wan S, Niu S et al (2010a) Increased temperature and precipitation interact to affect root production, mortality, and turnover in a temperate steppe: implications for ecosystem C cycling. Glob Change Biol. doi:10.1111/j.1365-2486.2009.02019.x

Bai Y, Wu J, Clark CM et al (2010b) Tradeoffs and thresholds in the effects of nitrogen addition on biodiversity and ecosystem functioning: evidence from inner Mongolia Grasslands. Glob Change Biol 16:358–372. doi:10.1111/j.1365-2486.2009.01950.x

Baldocchi DD, Xu LK, Nancy K (2004) How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland. Agric For Meteorol 123:13–39

Dorothy P (2000) Sensitivity and rapidity of vegetation response to abrupt climate change. Proc Natl Acad Sci U S A 97(4):1359–1361

Fan J, Zhong H, Harris W et al (2008) Carbon storage in the grasslands of China based on field measurements of above- and below-ground biomass. Clim Change 86:375–396. doi:10.1007/s10584-007-9316-6

Felzer BS, Reily J, Melillo J et al (2005) Future effects of ozone on carbon sequestration and climate change policy using a global biochemistry model. Clim Change 73:345–373

Flanagan LB, Linda LA, Carlson PJ (2002) Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate steppe. Glob Change Biol 8:599–615

Fu Y, Yu G, Sun X et al (2006) Depression of net ecosystem CO_2 exchange in semi-arid *Leymus chinensis* steppe and alpine shrub. Agric For Meteorol 137:234–244

Goodrich LE (1976) A numerical model for assessing the influence of snow cover on the ground thermal regime, Ph.D. thesis, 410 pp., McGill Univ., Montreal, Quebec

Hao Y, Wang Y, Sun X et al (2006) Seasonal variation and its ecological analysis of CO_2 exchange of *Leymus chinensis* steppe in Inner Mongolia. Sci China Ser D Earth Sci 36:174–382 (in Chinese)

Houghton RA (2007) Balancing the global carbon budget. Annu Rev Earth Planet Sci 35:313–347

Houghton RA, Hackler JL (1995) Continental scale estimates of the biotic carbon flux from land cover change: 1850-1980. ORNL/CDIAC-79, NDP-050, Carbon dioxide information analysis center. Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee

Houghton RA, Hackler JL (2003) Sources and sinks of carbon from land-use change in China. Glob Biogeochem Cyc 17:1034. doi:10.1029/2002GB001970

IPCC (2007) Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Kato T, Tang Y, Gu S et al (2004) Carbon dioxide exchange between the atmosphere and an alpine meadow ecosystem on the Qinghai-Tibetan Plateau, China. Agric For Meteorol 124:121–134

Lee R, Yu F, Price K, Ellis J, Shi P (2002) Evaluating vegetation phenological patterns in Inner Mongolia using NDVI time series analysis. Int J Remote Sens 23:2505–2512

Li SG, Asanuma J, Eugster W et al (2005) Net ecosystem carbon dioxide exchange over grazed steppe in central Mongolia. Glob Change Biol 11:1941–1955. doi:10.111/j.1365-2486.2005.01047.x

Liu M, Tian H (2010) China’s land-cover and land-use change from 1700 to 2005: estimations from high-resolution satellite data and historical archives. Glob Biogeochem Cyc 34:18. doi:10.1029/2009GB003687

Liu J, Tian H, Liu M, Zhuang D, Melillo JM, Zhang Z (2005) China’s changing landscape during the 1990s: large-scale land transformations estimated with satellite data. Geophys Res Lett 32:L02405. doi:10.1029/2004GL021649

Liu W, Zhang Z, Wan S (2009) Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland. Glob Change Biol 15:184–195

Lu N, Wilske B, Ni J, John R, Chen J (2009) Climate change in Inner Mongolia from 1955 to 2005: rends at regional, biome and local scales. Environ Research Letters 4:045006. doi:10.1088/1748-9326/4/4/045006

Lu C, Tian H, Liu M, Ren W, Xu X, Chen G, Zhang C (2012) Effect of nitrogen deposition on China’s terrestrial carbon uptake in the context of multifactor environmental changes. Ecol Appli 22(1):53–75

Ma W, Han M, Lin X, Ren Y, Wang Z, Fang J (2006) Carbon storage in vegetation of grasslands in Inner Mongolia. Chin J Arid Land Resour Environ 20(3):192–204 (in Chinese with English abstract)

Ma W, Fang J, Yang Y, Mohammat A (2010) Biomass carbon stocks and their changes in northern China’s grasslands during 1982-2006. Sci China Ser C Life Sci 53:841–850. doi:10.1007/s11427-010-4020-6

Meyers TP (2001) A comparison of summertime water and CO_2 fluxes over rangeland for well watered and drought conditions. Agric For Meteorol 106:205–214

Ni J (2001) Carbon storage in terrestrial ecosystems of China: estimates at different spatial resolutions and their responses to climate change. Clim Change 49:339–358

Ni J (2004) Forage yield-based carbon storage in grasslands of China. Clim Change 67:237–246

Niu S, Wu M, Han Y, Xia J, Li L, Wan S (2008) Water-mediated responses of ecosystem C fluxes to climatic change in a temperate steppe. New Phytol 177:209–219

Niu S, Wu M, Han Y et al (2009a) Nitrogen effects on net ecosystem carbon exchange in a temperate steppe. Glob Change Biol 16(1):144–155

Niu S, Yang H, Zhang Z et al (2009b) Non-additive effects of water and nitrogen addition on ecosystem carbon exchange in a temperate steppe. Ecosystems 12:915–926

Nosberger J, Blum H, Fuhrer J (2000) Crop ecosystem response to climatic change: productive grasslands In: Hodges H F, ed. Climate change and global crop productivity Wallingford UK: CAB International 271–291

Piao S, Fang J, Ciais P, Peylin P, Huang Y (2009) The carbon balance of terrestrial ecosystems in China. Nature 450:1009–1014

Qian W, Lin X, Zhu Y, Xu Y, Fu J (2007) Climatic regime shift and decadal anomalous events in China. Clim Change 84:167–189

Ren W, Tian H, Chen G et al (2007) Influence of ozone pollution and climate variability on grassland ecosystem productivity across China. Environ Pollu 149:327–335

Running SW (2008) Ecosystem disturbance, carbon, and climate. Science 321:652–653

Schönbach P, Wan H, Gierus M et al (2011) Grassland responses to grazing: effects of grazing intensity and management system in an Inner Mongolian steppe ecosystem. Plant Soil 340:103–115

Shi F, Li YE, Gao QJ et al (2009) Effects of managements on soil organic carbon of grassland in China. Pratacult Sci 26:9–15 (in Chinese with English abstract)

Sui X, Zhou G (2012) Carbon dynamics of temperate grassland ecosystems in China from 1951 to 2007: an analysis with a process-based biogeochemistry model. doi: 10.1007/s12665-012-1756-2

Thornton PE, Running SW (1999) An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. Agric For Meteorol 93:211–228

Thornton PE, Running SW, White MA (1997) Generating surfaces of daily meteorological variables over large regions of complex terrain. J Hydrol 190:214–251

Tian HQ, Melillo J, Lu C, Kicklighter DW et al (2011) China’s terrestrial carbon balance: contributions from multiple global change factors. Global Biogeochem Cyc 25:GB1007. doi:10.1029/2010GB003838

Wang SP, Wang YF, Li YH et al (1998) The influence of different stocking rates on herbage regrowth and aboveground net primary production. Acta Agrest Sin 6:275–281 (in Chinese with English abstract)

Wang S, Tian H, Liu J, Pan S (2003) Pattern and change of soil organic carbon storage in China: 1960s-1980s. Tellus 55B:416–427

Wang Y, Zhou G, Wang Y (2008) Environmental effects on net ecosystem CO_2 exchange at half-hour and month scales over *Stipa krylovii* steppe in northern China. Agric For Meteorol I48:714–722

Wang SP, Wilkes A, Zhang ZC et al (2011) Management and land use change effects on soil carbon in northern China's grasslands: a synthesis. Agri Ecosyst Environ 142(3–4):329–340

Wever LA, Flanagan LB, Carlson PJ (2002) Seasonal and inter-annual variation in evapotranspiration, energy balance, and surface conductance in northern temperate grassland. Agric For Meteorol 112:31–49

Xia J, Niu S, Wan S (2009) Response of ecosystem carbon exchange to warming and nitrogen addition during two hydrologically contrasting growing seasons in a temperate steppe. Glob Change Biol 15:1544–1556

Xiao X, Ojima DS, Parton WJ, Chen Z, Chen D (1995) Sensitivity of Inner Mongolia grasslands to climate change. J Biogeogr 22:643–648

Yang Y, Fang J, Ma W, Guo D, Mohammat A (2010a) Large-scale pattern of biomass partitioning across China's grasslands. Global Ecol Biogeogr 19:268–277. doi:10.1111/j.1466-8238.2009.00502.x

Yang Y, Fang J, Ma W et al (2010b) Soil carbon stock and its changes in northern China's grasslands from 1980s to 2000s. Glob Change Biol 16:3036–3047. doi:10.1111/j.1365-2486.2009.02123.x

Yang F, Zhou G, Hunt JE, Zhang F (2011) Biophysical regulation of net ecosystem carbon dioxide exchange over a temperate desert steppe in Inner Mongolia, China. Agri Ecosyst Environ 142:318–328

Yuan Z, Li L, Han X et al (2006) Nitrogen response efficiency increased monotonically with decreasing soil resource availability: a case study from a semi-arid grassland in northern China. Oecologia 148:564–572

Zhang X (eds.) (2007) Vegetation Map and Vegetation Regionalization Map of China (1:1 million), China Land Press

Zhuang Q, Romanovsky VE, McGuire AD (2001) Incorporation of a permafrost model into a large-scale ecosystem model: evaluation of temporal an spatial scaling issues in simulating soil thermal dynamics. J Geophy Res 106(D24):33,649–670

Zhuang Q, McGuire AD, Melillo JM et al (2003) Carbon cycling in extratropical terrestrial ecosystems of the northern hemisphere during the 20th Century: a modeling analysis of the influences of soil thermal dynamics. Tellus 55B:751–776