J Soils Sediments (2013) 13:1012–1023
DOI 10.1007/s11368-013-0675-5

SOILS, SEC 2 • GLOBAL CHANGE, ENVIRON RISK ASSESS, SUSTAINABLE LAND USE • RESEARCH ARTICLE

Effects of grazing on CO_2 balance in a semiarid steppe: field observations and modeling

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Received: 23 October 2012 / Accepted: 25 February 2013 / Published online: 14 March 2013

Abstract

Purpose Carbon (C) dynamics in grassland ecosystem contributes to regional and global fluxes in carbon dioxide (CO_2) concentrations. Grazing is one of the main structuring factors in grassland, but the impact of grazing on the C budget is still under debate. In this study, in situ net ecosystem CO_2 exchange (NEE) observations by the eddy covariance technique were integrated with a modified process-oriented biogeochemistry model (denitrification–decomposition) to investigate the impacts of grazing on the long-term C budget of semiarid grasslands.

Materials and methods NEE measurements were conducted in two adjacent grassland sites, non-grazing (NG) and moderate grazing (MG), during 2006–2007. We then used daily weather data for 1978–2007 in conjunction with soil properties and grazing scenarios as model inputs to simulate grassland productivity and C dynamics. The observed and simulated CO_2 fluxes under moderate grazing intensity were compared with those without grazing.

Results and discussion NEE data from 2-year observations showed that moderate grazing significantly decreased grassland ecosystem CO_2 release and shifted the ecosystem from a negative CO_2 balance (releasing 34.00 g $C m^{-2}$) at the NG site to a positive CO_2 balance (absorbing −43.02 g $C m^{-2}$) at the MG site. Supporting our experimental findings, the 30-year simulation also showed that moderate grazing significantly enhances the CO_2 uptake potential of the targeted grassland, shifting the ecosystem from a negative CO_2 balance (57.08 ± 16.45 g $C m^{-2} year^{-1}$) without grazing to a positive CO_2 balance (-28.58 ± 14.60 g $C m^{-2} year^{-1}$) under moderate grazing. The positive effects of grazing on CO_2 balance could primarily be attributed to an increase in productivity combined with a significant decrease of soil heterotrophic respiration and total ecosystem respiration.

Conclusions We conclude that moderate grazing prevails over no-management practices in maintaining CO_2 balance in semiarid grasslands, moderating and mitigating the negative effects of global climate change on the CO_2 balance in grassland ecosystems.

Keywords Carbon budget · DNDC · Eddy covariance · Grassland · Grazing · Soil heterotrophic respiration

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Responsible editor: Hailong Wang

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1 Introduction

Increasing human activity and global climatic and atmospheric changes have urged the need for understanding the role of ecosystem management in driving global carbon (C) budgets (Lang et al. 2011). Studies on C budgets of terrestrial ecosystems so far have mainly focused on peatlands and forests, while arid and semiarid grassland ecosystems have received much less attention, probably because of their relatively low productivity (LeCain et al. 2002). However, as one of the most widespread vegetation types, grasslands cover approximately 40 % of the land surface (Frank et al. 2000) and contain around 30 % of global total soil C stocks (Anderson 1991). Therefore, grasslands play an important role in the global C budget (Fan et al. 1998; Hunt et al. 2004). Hence, understanding the underlying mechanisms of C dynamics of the major grassland ecosystems of the world is needed in developing predictive global C cycle models and to accurately quantify global C budgets (Piao et al. 2007; Schimel 1995).

The Eurasian grassland region is the largest and most characteristic in the world, although the vegetation exhibits strong regional features. The typical steppe is widely distributed in the eastern Eurasian steppe zone, which occupies a total area of about 4.1×10^7 ha, of which more than half is located in China (Hao et al. 2008). Livestock grazing is the dominant management activity in this region, affecting the cycling of C and N via defoliation, excretal returns, and mechanical disturbance (Allard et al. 2007; Di et al. 2011; Schönbach et al. 2011). Grazing for example has strong potential to affect the C budget of grassland ecosystems through effects on C assimilation and ecosystem respiration (Cui et al. 2005b; Hafner et al. 2012). Animal grazing has fundamental effects on soil erosion and consequently on ecosystem carbon storage (Hoffmann et al. 2008; Schönbach et al. 2012). The loss of topsoil by soil erosion consequently leads to the loss of soil productivity (Zhao et al. 2006) and is therefore part of the soil degradation process in semiarid environments. Soil degradation affects the soil organic carbon, nitrogen dynamics (Mendez et al. 2006; Hoffmann et al. 2008), and soil carbon sequestration (Lal 2003). Besides, grazing plays an important role in modifying ecosystem physiological processes such as carbon fixation and respiration. By removing plant biomass, grazers often modify canopy structure and the energy balance of grasslands, with resulting feedbacks on soil temperature and soil water balance (Zhou et al. 2007) and, ultimately, on net C uptake (Soussana et al. 2007). Grazers can also indirectly alter plant community composition through their diet selectivity (Augustine and McNaughton 1998), and consequently influence soil C inputs (De Deyn et al. 2008). So far, the effects of grazing on the net C budget and ecosystem processes controlling C cycling and allocation in native grassland ecosystems are inconclusive. For example, a reduction in aboveground plant biomass by grazing may reduce net C uptake (Frank et al. 2000), and a decline of C sequestration capacity of grassland ecosystems upon grazing activity has repeatedly been shown (e.g., Frank 2002; Nieveen et al. 2005). On the contrary, in a long-term grazing experiment in US shortgrass prairie, LeCain et al. (2002) did not find any changes in photosynthetic, soil respiration, and net CO_2 exchange rates between grazed pastures and exclosures. Therefore, in order to accurately predict ecosystem C budgets, we clearly must better understand how disturbances like grazing affect the seasonal inter-annual variation in CO_2 exchange.

Recently, the eddy covariance (EC) technique, a micrometeorological method, has become widely used to measure the net exchanges of CO_2, water, and energy between plant–soil system and the atmosphere, with reliable results over various spatial and temporal scales (Baldocchi et al. 2001; Hao et al. 2011). Net ecosystem CO_2 exchange (NEE) is an important component of the C cycle of grassland ecosystems, which physiologically determines whether the ecosystem functions as a sink or a source for atmospheric CO_2, besides soil erosion. The observed fluxes of NEE provide valuable information for understanding photosynthesis as well as respiration at the ecosystem scale (Falge et al. 2002). However, the EC method is still relatively new and so far only a limited amount of data have been accumulated. Moreover, complex interactions between the primary drivers of grassland C dynamics, including climate, soil, vegetation, and human activity, make it difficult to reveal the mechanisms controlling C dynamics (Kurbatova et al. 2008). A further complication is that EC C flux data cannot distinguish between the specific physiological processes and partition respiration of ecosystems into autotrophic respiration and heterotrophic respiration underlying observed NEE variations (Li et al. 2007). Therefore, an integrated approach of EC measurements and complementary modeling studies is needed in unraveling the underlying mechanisms and effectively predicting the long-term effects of grazing on grassland ecosystem CO_2 fluxes.

In this study, we tested the effects of two contrasting grazing treatments on in situ NEE fluxes by using EC techniques for two consecutive years. The short-term empirical data were then integrated with results from a validated process-based biogeochemical model (Kang et al. 2011), denitrification–decomposition (DNDC), to investigate the long-term effects of grazing on the CO_2 balance of the semiarid grasslands in Inner Mongolia, China. We specifically tested whether moderate grazing can mitigate the negative effects of global climate change on the CO_2 balance in grassland ecosystems. Our integrated approach provides substantial insights into the response and C feedback mechanisms of the steppe ecosystem to grazing management and contributes to more accurate predictions of the functioning of steppe ecosystems under future climate scenarios.

2 Materials and methods

2.1 Field sites

Net ecosystem CO_2 exchange was measured using the EC technique in two adjacent grassland sites (moderate grazing, non-grazing) located at the Xilin River Watershed in the Inner Mongolia Autonomous Region, China in 2006–2007 (43°32′N, 116°40′E, 1,200 m above sea level) (Fig. 1). The sites are located about 2 km apart from each other and belong to the typical climate zone of semiarid continental temperate steppe, with cold and dry winters and warm and moist summers. The two sites experience similar climatic conditions with a multi-year (1978–2007) average annual temperature of 0.9 °C and annual precipitation of 338 mm. The annual precipitation (rainfall and snowfall) was 291.6 and 177.8 mm for 2006 and 2007, respectively.

The non-grazing (NG) site (400×600 m) is located at typical *Leymus chinensis* steppe, which has been fenced off since 1979. The soil is dominated by dark chestnut (Mollisol) with a depth of 100–150 cm and contains 21 % clay, 60 % sand, and 19 % silt (Wang and Cai 1988). As a result of exclusion of grazing, a thick litter layer has accumulated on the soil surface. Soil porosity is 0.53 m^3m^{-3}, and the field capacity is 0.29 m^3m^{-3}, with a wilting point of 0.12 m^3m^{-3} for the top 20 cm soil layer. The xeric rhizomatous grass *L. chinensis* is the constructive species with *Stipa grandis*, *Agropyron cristatum*, *Cleistogenes squarrosa*, and *Carex duriuscula* being codominant. Plant community cover is about 25 % and can reach up to 50 % in wet years (Xiao et al. 1995). The peak standing height of the grass clusters is approximately 50–60 cm.

The moderate grazing (MG) site is grazed by sheep (four sheep/ha) year round except for October. Fewer plant species occur in the MG site than in the NG site. But, as for the NG site, *L. chinensis*, *S. grandis*, and *C. squarrosa* are the most dominant species at the MG site. *Artemisia frigida*, *Potentilla acaulis*, and *Chenopodium glaucum* account for a large proportion of total plant individuals but their contribution to total biomass is relatively small. Plant community cover is about 10–15 %. At the MG site, there is nearly no litter accumulation. The peak standing height of the grass clusters is approximately 20–30 cm.

2.2 Eddy covariance measurements

Both at the NG and MG sites, field measurements of NEE fluxes were conducted continuously using EC towers from 1 May 2006 to 30 September 2007. The fetch from all directions was more than 200 m based on calculations with a footprint model (Kljun et al. 2004). Briefly, a three-axis sonic anemometer (model CSAT3, Campbell Scientific, MS, USA) with an open path infrared CO_2/H_2O gas analyzer (IRGA, LI 7500, LI-COR Inc. NE, USA) was installed at a height of 2.2 m above ground level to measure the CO_2 fluxes. The instrument provided high frequency measurements (10 Hz), and the turbulent flux data were recorded as half-hour averages by a datalogger (CR5000, Campbell Scientific).

Some environmental factors used for gap-filling calculations were measured nearby the EC tower. Precipitation was collected at a height of 1.5 m above ground level and was measured by a tipping bucket rain gauge (TE525MM, Campbell Scientific). Soil temperature was measured at five depths (0.05, 0.10, 0.20, 0.50, and 1.0 m) by copper–constantan thermocouples. Soil volumetric water content was measured by time-domain reflectometer probes at 0.05, 0.2, and 0.5 m depth. Cup anemometers (034A-L and 014A; Traverse, MI, USA) at 1.5 and 2.5 m above ground level

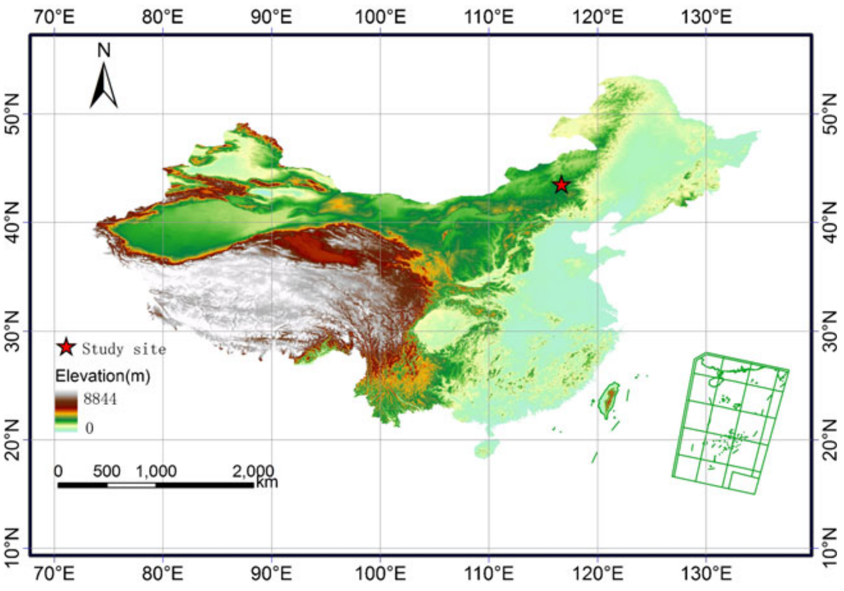

Fig. 1 Location of study sites in an *L. chinensis* steppe in Inner Mongolia, China

were used to measure wind speed. All meteorological data from the sensors were collected and stored in a digital datalogger (CR23X; Campbell Scientific).

2.3 Data quality control and processing

Uncertainties in long-term flux measurements may result from instrument failure or from adverse atmospheric conditions. To reduce the measurement-induced uncertainties, all flux data were quality controlled by adjusting the data by the Webb, Pearman, and Leuning algorithm (Webb et al. 1980). To ensure optimal data quality, time series for the flux data of CO_2 (Fc), latent heat (LE), and sensible heat (HS) measured during the rainfall or snowfall events or the instrument malfunctions (e.g., system maintenance, power outages, etc.) were excluded to eliminate inaccurate data. Since low u^* and weak turbulence can result in underestimation of the CO_2 exchange rates (Jaksic et al. 2006), only flux data with u^* greater than 0.2 $\mathrm{m\,s^{-1}}$ were used. After data quality control, approximately 30 % of the data obtained from the two EC towers were excluded. To fill the data gaps and calculate daily and annual sums of the fluxes, gap-filling approaches, such as the mean diurnal variation (MDV; Falge et al. 2001) and the interpolation methods developed by Aubinet et al. (2002), were adopted. The gaps introduced were filled using several strategies. For longer gaps, empirical formulas describing relationships between PAR, soil temperature, and net ecosystem CO_2 flux were applied separately for daytime and nighttime. In cases where empirical relationships could not be developed as a result of missing meteorological data, MDV method was used to fill the gap (Falge et al. 2001). The details of the flux data processing have been described by Hao et al. (2007).

The integrated daily NEE is the sum of the daytime net ecosystem CO_2 exchange ($\mathrm{NEE_{day}}$) and the nighttime net ecosystem CO_2 exchange ($\mathrm{NEE_{night}}$):

$$\mathrm{NEE} = \mathrm{NEE_{day}} + \mathrm{NEE_{night}} \qquad (1)$$

where the positive and negative values of observed NEE represent net loss and gain of CO_2 by the soil–plant–atmosphere system and are termed “negative CO_2 balance” and “positive CO_2 balance,” respectively. $\mathrm{NEE_{day}}$ represents the sum of two component fluxes: gross primary productivity (GPP) and total ecosystem respiration (R_e). At night, GPP is 0, and hence, $\mathrm{NEE_{night}}$ is equal to total ecosystem respiration.

2.4 DNDC model

The DNDC model is a comprehensive process-oriented biogeochemistry model, which has been globally used to simulate crop growth and soil C and N dynamics based on the input data on soil properties, climate, and farming practices. Originally, it was developed to quantify C sequestration and trace gas emissions from agricultural soils (Li et al. 1992a, b). Thereafter, it has been modified and further expanded to simulate the biogeochemical cycling of C and N of forests, wetlands, and grasslands (Cui et al. 2005a; Li et al. 1996; Xu-Ri et al. 2003).

The DNDC model consists of two components and six submodels for simulating soil climate, plant growth, soil organic matter decomposition, nitrification, denitrification, and fermentation, respectively (Giltrap et al. 2010; Li et al. 2007). The core of DNDC is a soil biogeochemistry model describing carbon and nitrogen transport and transformation driven by a series of soil environmental factors, such as temperature, moisture, redox potential (Eh), pH, and substrate concentration gradients, and anthropogenic activities such as grassland management. Detailed management measures (e.g., fencing, grazing, cutting, fertilization, irrigation) have been parameterized and linked to the various biogeochemical processes embedded in DNDC.

In DNDC, the dynamics of the C budgets are controlled by the balance between C uptake by photosynthesis and C loss by respiration. As most C models, DNDC simulates ecosystem C dynamics by tracking plant growth, litter incorporation, and soil heterotrophic respiration. DNDC simulates plant growth driven by the air temperature and soil water and N availability at daily time steps by tracking photosynthesis, respiration, water and N demand, C allocation, crop yield, and litter production. During the simulated growing seasons, daily N demand is calculated based on the total N demand, daily temperature, and thermal degree days. Daily water demand is calculated based on the daily N demand, daily potential biomass growth, and water requirement. If there is not enough water or N to meet the demand, water stress or N stress will occur reducing the daily plant biomass production. The increase in plant biomass production will be partitioned into the grain, shoot (leaf + stem), and root pools of the plant at a daily time step. The plant continuously assimilates the atmospheric CO_2 into the biomass C and partitions it to the grain, leaves, stems, and roots every day. When plants reach maturity or the temperature drops below 0 °C, senescence will start. All the root litter will be incorporated in the soil profile and the aboveground residue allocated in the top soil during the senescence. As soon as the litter is incorporated in the simulated soil profile, DNDC will partition the litter into three soil litter pools on basis of the C/N ratio of the litter, namely very labile litter, labile litter, and recalcitrant litter, on the basis of C/N ratio of the litter. During decomposition of the litter, part of the litter C is consumed by the soil microorganisms and hence converts the litter to CO_2, and part of the litter C is turned into the microbial biomass. After death of the microorganisms, the microbial remains undergo further decomposition. During the sequential decomposing processes, part of the organic C becomes CO_2 to be emitted into the atmosphere. So, for the entire plant–soil–atmospheric system, if the CO$_2$ uptake rate is higher than the CO$_2$ emission rate, the ecosystem will gain CO$_2$; otherwise, the ecosystem will release CO$_2$.

The improvement of this study is the application of grazing management system. In the current DNDC implementation, the influence of grazing on plant biomass is addressed by balancing animal food demand with the amount of aboveground biomass. Grazing in the model can be parameterized to consume defined daily amounts of aboveground live and dead standing plant biomass. The total daily C and N deposits are specified, allowing for simulation of losses through animal carcasses and milk, and input by dung and urine into the soil litter pools. In addition, the DNDC model has a “water retention layer” function for grazed pastures, which simulates effects of soil compaction from cattle treading on water flow.

As a national experimental station, the Xilinhot site has accumulated records of the local vegetation and management practices. Based on the long-term local observations, we generalized and defined several site-specific parameters such as maximum yield, biomass partitions in the above- and belowground parts, C/N for the above- and belowground parts, cumulative thermal degree days, N fixation index, soil properties, and anthropogenic activities including enclosure and grazing. To distinguish the impacts of grazing, we set two alternative grassland management scenarios: NG and MG scenario. Under the NG scenario, we defined that the grassland was fenced without any human and grazing activity such that all plant biomass would eventually be incorporated into the soil. Under the MG scenario, we defined that the grazing intensity was four sheep/ha (corresponding with the moderate grazing intensity at our experimental field site) and the grazing time was set year round except for October. During the grazing periods, 1.65 kg dry matter ha^{-1} day^{-1} is taken up per sheep (Wang and Li 1997). Nutrient use efficiency by sheep was set to 68 % for C and 6 % for N. The total daily C deposit and N deposit are 0.54 kg C ha^{-1} day^{-1} and 0.04 kg N ha^{-1} day^{-1}, respectively. Deposited nitrogen in feces is split into 60 % urine and 40 % dung. The C/N ratio for dung is 16 and the C/N ratio for urine is 0.5. Daily weather data of air temperature and precipitation were collected for a 30-year period (1978 to 2007) to support the simulations. The simulation capacity of the DNDC model for *L. chinensis* steppe has been validated (Kang et al. 2011). Given the good performance of the model, especially the modeled responses of NEE fluxes to climatic variation, we utilized the DNDC model to quantify the impacts of several long-term grazing management practices (during 1978–2007) on the C budget for semiarid grasslands in the region of study.

2.5 Statistical analysis

Statistical significances of the effects of moderate grazing on observed soil moisture and CO$_2$ fluxes and modeled CO$_2$ fluxes (Table 1) were determined separately by analysis of *t* test using a standard statistical analysis software SPSS (Version 13.0, SPSS, Chicago, IL, USA). Least significance difference was used to separate the means when differences were significant. Significance was assumed at the $P=0.05$ level. Simple correlations and regression analysis between some variables were performed.

3 Results

3.1 Field observations

Moderate grazing significantly affected the growing season C balance of the targeted grassland ecosystem (Fig. 2). At the NG site, the days when CO$_2$ was emitted to the atmosphere mostly occurred during the early rapid growth and late senescence stages over 2006–2007 (i.e., positive NEE; Fig. 2). Just after winter dormancy, daily NEE differed greatly between the 2 years (peak loss values: 2.44 g C m^{-2} day^{-1} in 2006, 2.17 g C m^{-2} day^{-1} in 2007). At the MG site, CO$_2$ emission significantly decreased, C fixation capability distinctly strengthened, and the ecosystem reached maximum uptake values of daily CO$_2$ fluxes (−1.3 g C m^{-2} day^{-1} in 2006 and −1.55 g C m^{-2} day^{-1} in 2007) in late-July, and began to release CO$_2$ by mid-August in 2006 and by mid-September in 2007. Compared to the non-grazing management, moderate grazing increased the annual number of days the ecosystem was a C sink (38 days in 2006 and 107 days in 2007). As indicated by lower NEE values (see Fig. 2a, b), moderate grazing significantly enhanced ecosystem C fixation both in 2006 ($P<0.0001$) and

Table 1 The simulated 30-year mean C budget (in gram C per square meter per year) under non-grazing (NG) and moderate grazing (MG) scenarios for a *L. chinensis* steppe in Inner Mongolia, China over 1978–2007

CO$_2$ fluxes	NG scenario	MG scenario	*P* values	*T* values
GPP	327.14±29.43	346.41±28.55	0.822	−0.226
R_{shoot}	69.85±6.71	70.94±6.33	0.906	−0.118
R_{root}	107.70±8.12	110.20±7.65	0.823	−0.224
R_{a}	177.55±14.77	181.14±13.93	0.86	−0.177
R_{h}	206.67±6.98	136.68±3.27	<0.001*	9.085
R_{e}	384.22±16.54	317.82±14.78	0.004**	2.994
Litter	120.36±8.93	76.47±8.49	0.001*	3.562
NEE	57.08±16.45	−28.58±14.60	0.001*	3.439

GPP gross primary productivity, R_{e} ecosystem respiration, *NEE* net ecosystem exchange (negative values indicate fixation of CO$_2$ or C, while positive values denote a net release of CO$_2$ or C), R_{shoot} shoot respiration, R_{root} root respiration, R_{a} plant autotrophic respiration, R_{h} soil heterotrophic respiration

*$P<0.001$; **$P<0.01$ (significant)

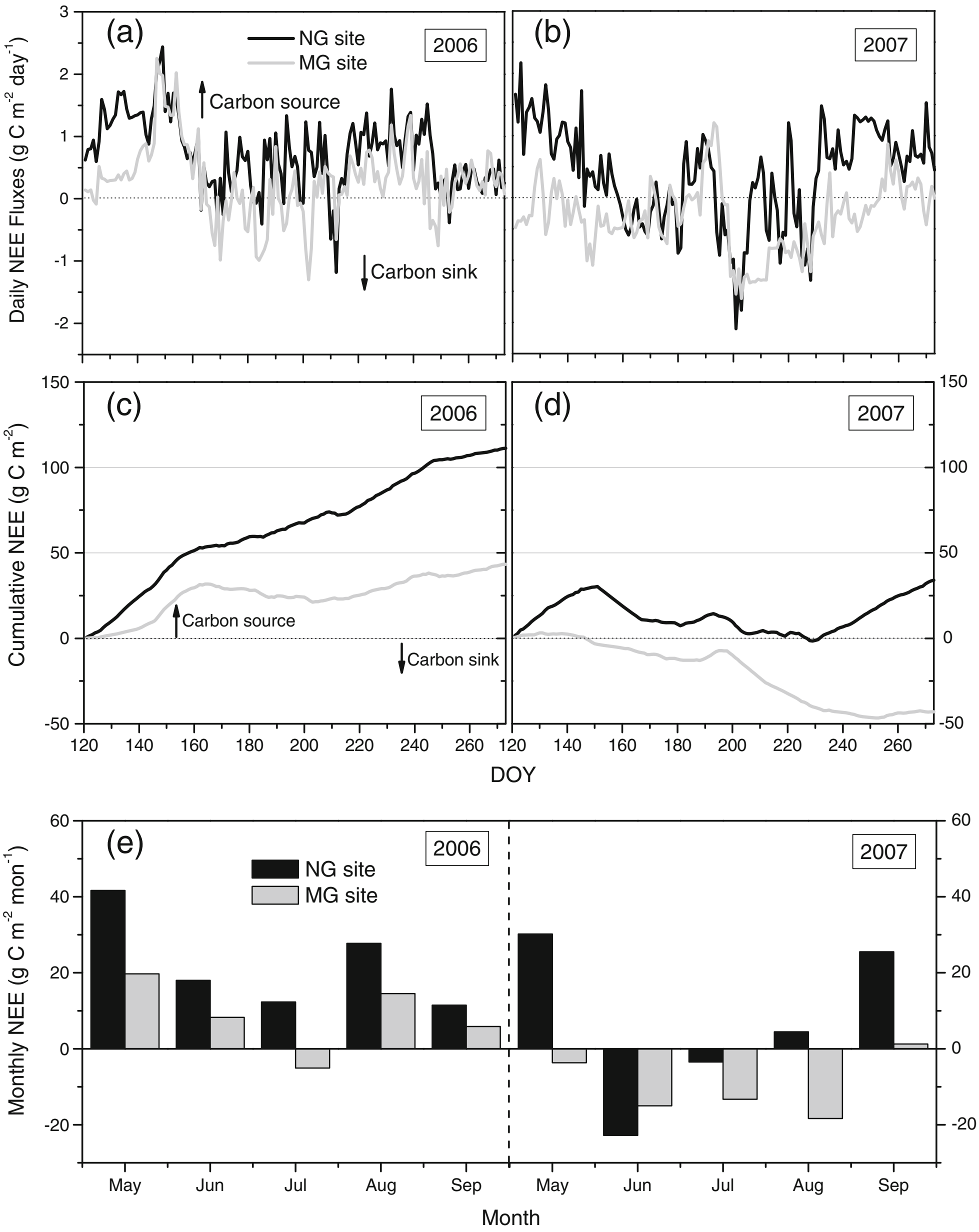

Fig. 2 The seasonal variation in **a**, **b** daily; **c**, **d** cumulative; and **e** monthly net ecosystem CO_2 exchange (NEE) fluxes (in gram C per square meter per month) at the non-grazing site (*black*) and the moderate grazing site (*gray*) for a *L. chinensis* steppe in Inner Mongolia, China in the 2006 and 2007 growing season. Positive and negative NEE values represent net loss and gain of carbon by the soil–plant–atmosphere system, respectively. *DOY*, day of year; *NG*, non-grazing; *MG*, moderate grazing

2007 ($P<0.0001$). Cumulative NEE fluxes showed that the NG site was a net C source during both the 2006 and 2007 growing season, releasing a total of 111 and 34 g Cm^{-2}, respectively (see Fig. 2c, d). In contrast, the MG site was a net C source during the 2006 growing season but released ±60 % less C to the atmosphere than the NG site. Moreover, during the 2007 growing season, the MG site was a net C sink, sequestering 43 g Cm^{-2}.

Monthly integrated NEE fluxes also showed that moderate grazing significantly and strongly altered the C dynamics of the steppe ecosystem ($P<0.05$; Fig. 2e). For the 2006 growing season, the NG site was a C source, ranging from 11.46 to 41.69 g C$\mathrm{m}^{-2}\mathrm{month}^{-1}$. For most of the 2006 growing season, the MG site was also a C source, but net C loss at the MG site was consistently lower than at the NG site. In July 2006, the MG site was a C sink (−5.04 g Cm^{-2}), while the NG site was a C source (12.35 g Cm^{-2}). For the 2007 growing season, the NG site was a C source early and late during the season, but a C sink in between. The MG site was a C sink for most of the growing season; only in September, the MG site was a small C source. Except for June, the MG site either released less or absorbed more C than the NG site.

Moderate grazing significantly reduced soil water content in the 2006 ($P<0.0001$) and 2007 growing season ($P<0.0001$). Soil water content at 0–20 cm soil depth was higher in the NG site than in the MG site during most of 2006 and 2007 growing seasons. The impact of grazing on soil water content was greatest in September and October 2006 and in April and May 2007 (Fig. 3).

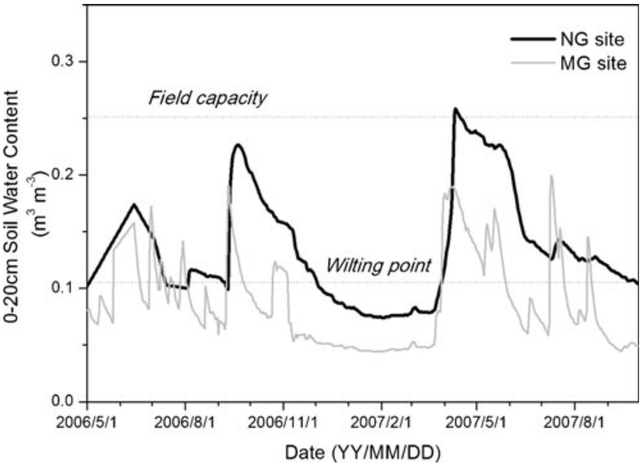

Fig. 3 The seasonal variation of daily mean soil water content (SWC) at 0–20 cm soil depth during 2006–2007 growing season in the non-grazing and grazing grassland. *NG*, non-grazing; *MG*, moderate grazing

3.2 Model simulations

3.2.1 Observed long-term climate conditions

Mean annual air temperature ranged from −1.3 °C in 1985 to 2.2 °C in 2007, with a mean of 0.9 °C and a coefficient of variation (CV) of 100 % for the 1978–2007 period (Fig. 4). Over the 30-year period, there was a significant increase in mean annual temperature (R^2=0.24; P=0.006) and in oscillation frequency. Mean annual precipitation varied from 163 mm in 2005 (extreme drought) to 507 mm in 1998, with a mean of 338 mm for the 1978–2007 period (see Fig. 4). On average, 89 % of annual precipitation was concentrated in the growing season (May to September). The CV in annual precipitation was 26.1 %. Mean annual precipitation strongly fluctuated over time, but there was a trend towards a decrease in mean annual precipitation for the 1978–2007 period (R^2=0.10; P=0.079; Fig.4). In summary, the *L. chinensis* steppe site of our study experienced a general trend of warming and reduced annual precipitation for the 1978–2007 period.

3.2.2 The impacts of moderate grazing on ecosystem C fluxes

Daily weather data in conjunction with soil properties and management practices were used as model inputs to simulate grassland productivity and soil C dynamics for the 1978–2007 period. The inter-annual and mean annual NEE, GPP, and ecosystem respiration (R_e), heterotrophic respiration, plant autotrophic respiration, and litter input under MG were compared with those under a NG scenario.

Comparison of CO_2 fluxes between the MG and NG scenario showed that moderate grazing altered the inter-annual dynamics of NEE and its components GPP and R_e (Fig. 5a–c). Under the NG scenario, the ecosystem on average was a source of atmospheric CO_2 with a mean annual emission of 57.08±16.45 g $Cm^{-2}year^{-1}$. In contrast, under the MG scenario, the ecosystem on average was a sink of atmospheric CO_2 with a mean annual uptake of 28.58±14.60 g $Cm^{-2}year^{-1}$ (see Table 1). Under both scenarios, NEE strongly fluctuated, but there was a trend of increasing NEE over time (R^2=0.19; P=0.019); under the MG scenario, the slope was slightly smaller than under the NG scenario (R^2=0.17; P=0.022). Moderate grazing significantly enhanced the C sequestration capacity of the grassland ecosystem compared to the NG scenario; MG basically converted the ecosystem from a C source to a C sink (Fig. 5a, Table 1). Enhanced C sequestration under the

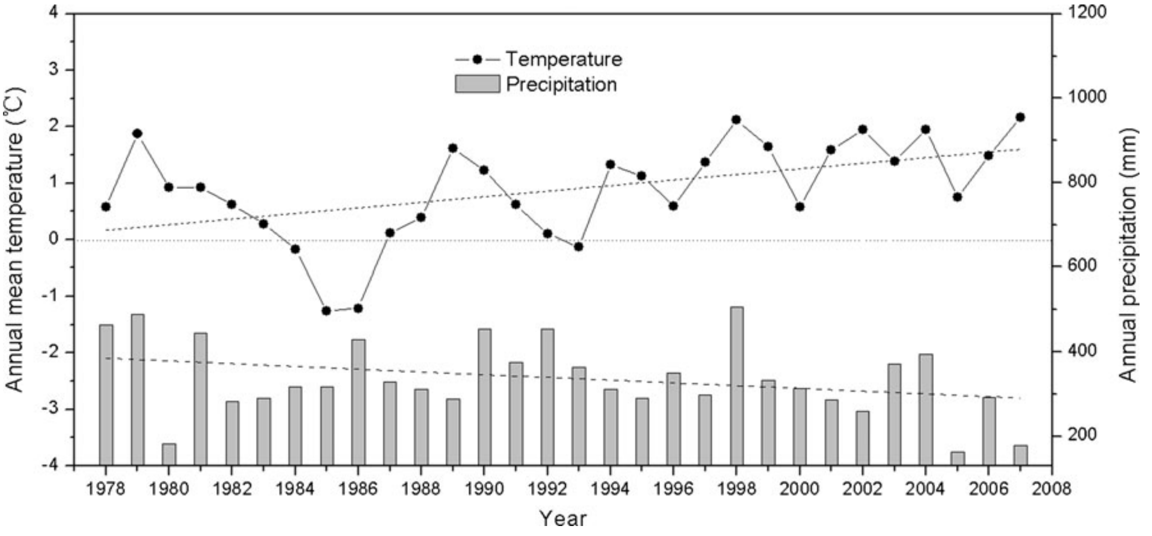

Fig. 4 The inter-annual variation in annual mean air temperature and precipitation at the study site over 1978–2007; *dashed lines* are the 30-year linear trend of annual mean air temperature and precipitation

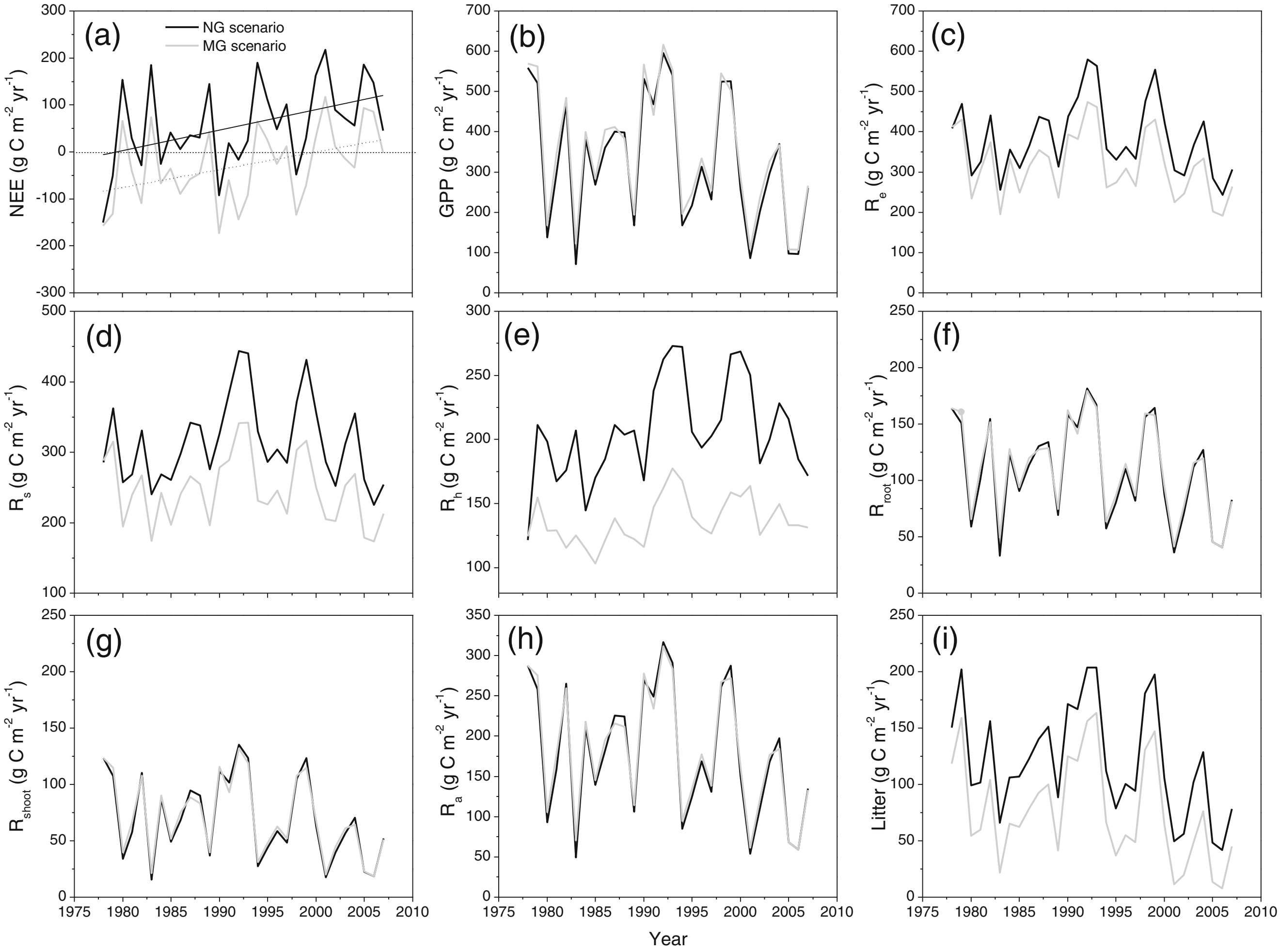

Fig. 5 The simulated inter-annual variation in **a** net ecosystem CO_2 exchange (NEE); **b** gross primary productivity (GPP); **c** ecosystem respiration (R_e); **d** soil respiration (R_s); **e** soil heterotrophic respiration (R_h); **f** root respiration (R_{root}); **g** shoot respiration (R_{shoot}); **h** plant autotrophic respiration (R_a); and **i** litter production/accumulation for a *L. chinensis* steppe in Inner Mongolia, China under non-grazing and moderate grazing scenarios over a 30-year period (1978–2007). *Solid line* and *dashed line* are the 30-year linear trends of annual NEE for the NG scenario and the MG scenario, respectively. *NG*, non-grazing; *MG*, moderate grazing

MG scenario could be largely attributed to a reduction in ecosystem respiration. Simulated R_e values under the MG scenario were significantly lower (minus 17 %) than under the NG scenario (see Fig. 5c, Table 1). Additionally, moderate grazing slightly increased GPP by approximately 6 %, but the difference between the MG and NG scenario was not statistically significant (see Fig. 5b, Table 1).

The model simulations showed that moderate grazing significantly decreased soil respiration (R_s) and heterotrophic respiration (R_h) by about 25 and 34 % compared to the NG scenario, respectively (see Fig. 5d–e, Table 1). Effects of moderate grazing on R_h could be attributed to a reduction in litter input. Litter C input under the MG scenario was significantly decreased by 36 % in comparison with the NG scenario (see Fig. 5i, Table 1). Plant autotrophic respiration (R_a) and its components shoot respiration (R_{shoot}) and root respiration (R_{root}) did not differ between the MG and NG scenarios (see Fig. 5f–h, Table 1). The annual differences between the MG and NG scenario in R_h and R_e were strongly positively correlated (Fig. 6a), as were the annual differences between the MG and NG scenario in R_h and NEE (see Fig. 6b).

4 Discussion

The increase in atmospheric concentration of CO_2 by 31 % since 1750 from fossil fuel combustion and land use change necessitates identification of strategies for mitigating the threat of the attendant global climate change (such as warming and drying) (Lal 2004). In this study, we will utilize the modeling approach (DNDC model) to explore alternative management opportunities such as grazing to find out to what degree we could moderate the negative

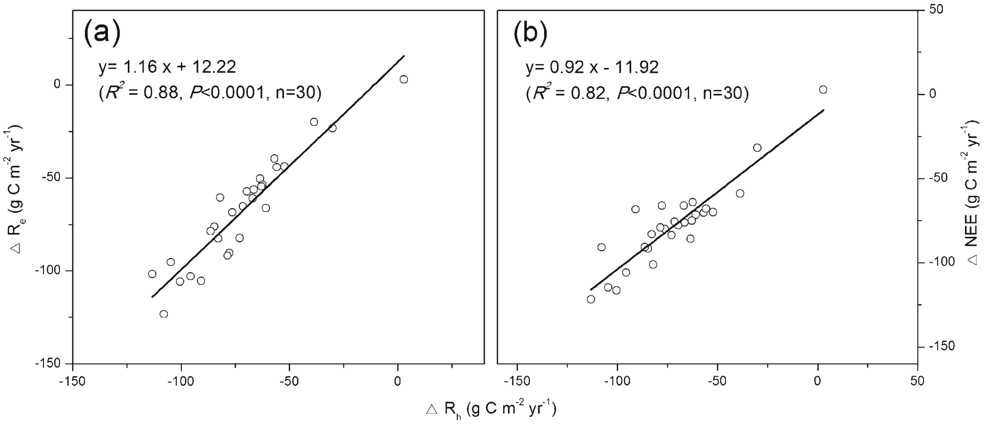

Fig. 6 The relationship between change in soil heterotrophic respiration (ΔR_h) and **a** change in ecosystem respiration (ΔR_e); **b** change in NEE (ΔNEE) in response to moderate grazing for a *L. chinensis* steppe in Inner Mongolia, China during 1978–2007

effects of climate change through improving our grassland management practice. The DNDC model, as a process-oriented biogeochemistry model, has been used to simulate and predict the dynamics of C budget for the semiarid grassland ecosystem (Kang et al. 2011). The modeled and observed CO_2 fluxes data were well in agreement ($P<0.0001$), both showing that the grassland shifted from positive to negative CO_2 balance from a wet year (2004) to a dry year (2005) over growing season. Furthermore, 100-year simulations found that, under the least human's disturbance conditions, a cooler or wetter future climate would substantially elevate the CO_2 uptake capacity of the grassland. However, the CO_2 uptake potential could significantly decrease and even become negative to turn the ecosystem to a negative CO_2 balance if the climate turned to be warmer and/or drier in the coming 100 years. In addition, we realized that the current grassland C dynamics in China are affected by a number of factors including climate change and land use management. So, in this study, we built on these previous findings and integrated 2-year field measurements with a 30-year modeling exercise showing that moderate grazing significantly altered NEE fluxes. We showed that moderate grazing even can reverse the steppe ecosystem from a negative to a positive CO_2 balance. Our findings are in accordance with the EC observed results of Li et al. (2005) who also found that grazing had a positive effect on C sequestration in the steppe in central Mongolia. Considering C removed by grazing, they calculated that the grassland ecosystem was a strong sink (−62 g C m^{-2} year^{-1}) under grazing management and a weak C source (20 g C m^{-2} year^{-1}) under non-grazing conditions. However, Wiesmeier et al. (2011, 2012a, 2012b) and Schönbach et al. (2012) found a clear increase of SOC of 30 % compared to grazed sites only based on the soil system at the same ungrazed site (ungrazed *Leymus*-dominated grassland, fenced in 1979) but different grazed site.

Our results suggest that the effects of grazing on the C dynamics of the grassland ecosystem have resulted from changes in GPP and/or R_e. The EC field observations provided only net C fluxes, whereas with the DNDC model, we could calculate GPP and R_e (by simulating autotrophic and heterotrophic respiration) at various time steps. Results from model simulations in the study revealed that grazing slightly increased GPP of the grassland ecosystem although not significant, indicating a stimulation of plant growth in *L. chinensis* steppe. Several previous studies, including both field and controlled pot experiments (e.g., Cui et al. 2005a; Schönbach et al. 2011; Wang and Wang 2001) as well as model simulations (e.g., Augustine and McNaughton et al. 1998; Leriche et al. 2001) also reported positive effects of grazing on plant productivity, such that GPP of grazed grassland ecosystems can be maintained (compensatory growth) or stimulated (overcompensatory growth). For example, using the CENTURY model, Wang et al. (2008) simulated the potential changes in net primary productivity (NPP) of *L. chinensis* steppe under different grazing intensities. They found that grazing (removing 10 % of the live shoots per month) slightly increased NPP by about 3 % compared with non-grazing conditions. This suggested that moderate grazing intensity can stimulate plant growth in *L. chinensis* steppe. The underlying mechanisms of compensatory or overcompensatory responses include (1) improvement of light availability by means of decreasing aboveground litter and self-shading, increasing light transmittance and photosynthetic rates in remaining leaves; (2) removal of inefficient vegetation tissue consuming carbohydrate and other resources to providing more nutrients for remaining tissues; and (3) reduction of the rate of senescence of remaining leaves and stimulation of plant growth by animal saliva (LeCain et al. 2000; McNaughton 1983).

The DNDC model showed that moderate grazing not only stimulated plant production but also decreased R_e. Moderate grazing significantly decreased R_e by about 17 %. Consistent with our studies, Polley et al. (2008) showed that grazing of mixed-grass prairie in North Dakota, USA, increased the C sequestration capacity by reducing R_e relatively more than daytime ecosystem CO_2 exchange (NEE_{day}). Furthermore, grazing affects ecosystem respiration directly or indirectly through affecting its individual components such as plant respiration and soil heterotrophic respiration. The modeled results showed that grazing significantly reduced R_h by about 34 % compared with non-grazing conditions, and changes in R_h explained 88 % of the change in R_e and 82 % of the change in NEE in our steppe ecosystem. This suggests that the effects of grazing on the net ecosystem C budget in our study mainly resulted from reduced aboveground litter input (see Fig. 5i) and then decreased soil heterotrophic respiration (see Fig. 5e), and less from stimulating plant growth (overcompensatory growth).

Since a significant fraction of R_h is attributable to the decomposition of plant litter, soil heterotrophic respiration usually decreases with litter removal. In our study, we found that litter C input under the MG scenario was significantly decreased by 36 % in comparison with the NG scenario due to the effects of moderate grazing. Grazing can affect microbial community composition and activity, and by that soil respiration directly by increasing soil compaction (Chen and Wang 2000), decreasing soil porosity and soil water content (Risch et al. 2007; Zhao et al. 2011), return of organic matter and nutrient to the soil in relatively labile forms as dung and urine (Augustine and McNaughton 1998), and by affecting soil microclimate and microbial biomass carbon (Liu et al. 2012; Rui et al. 2011). Grazing can also affect soil respiration indirectly by removing live plant biomass and, hence, decreasing substrate availability for soil biota (Wan and Luo 2003), or by altering plant community composition and canopy structure, which in turn can affect the chemical composition of litter input into the soil (Lecain et al. 2000; Schönbach et al. 2011; Sun et al. 2011).

It is worth to note that wind erosion plays a strong role in soil C storage and ecosystem C sink/source function in this semiarid grassland (Hoffmann et al. 2008; Wiesmeier et al. 2011, 2012a, 2012b; Steffens et al. 2011; Kölbl et al. 2011; Schönbach et al. 2012; Wu et al. 2012). The relatively small C gain by lower heterotrophic respiration in 2006 and 2007 at MG site is by far counterbalanced by a strong decline of C storage due to wind erosion at NG site (Hoffmann et al. 2008). Therefore, both observation and modeling methods should be further improved to include soil erosion for accurate explanation and prediction of ecosystem C balance. And we also should note that CO_2 measurements of only 2 years are not sufficient to obtain information about the long-term C development, as this environment has a high climatic variability. So, future work should focus on the long-term continuous measurements in the semiarid grassland ecosystem.

5 Conclusions

In summary, both the field observations and the modeling study demonstrated a higher potential of C fixation under moderate grazing than under non-grazing management; hence, moderate grazing prevails over non-grazing practices in maintaining CO_2 balance in semiarid grasslands, promoting both sustainable livestock production and ecosystem functioning. Recently, due to the rising levels of atmospheric greenhouse gases, global mean surface temperature is projected to increase between 1.8 and 4.0 °C over the next 100 years, and precipitation is expected to become more spatially and temporally variable (IPCC 2007). These climatic changes will significantly alter the C budget of grassland ecosystems, decrease the plant production, and increase ecosystem respiration (Kang et al. 2011; Zhang et al. 2005). However, alternative and appropriate grazing management practices in the targeted grassland can be beneficial to increasing CO_2 uptake, decreasing ecosystem CO_2 losses through erosion and emission, and even converting the grassland ecosystem from a negative CO_2 balance to a positive CO_2 balance. Therefore, we conclude that moderate grazing can moderate and mitigate the negative effects of global climate change on the CO_2 balance in grassland ecosystems. Moreover, carbon removed by grazing is essential for livestock production. Hence, moderate grazing outmatches grassland practice of exclusion of utilization, taking into consideration of both sustainable livestock production and ecosystem C maintenance. Furthermore, because of the strong role of soil erosion in this semiarid environment, future works would also focus on the effects of soil erosion on CO_2 balance for accurate explanation and prediction of ecosystem C balance. In addition, because the tower measurements only represent fluxes at the scale of the tower footprint (i.e., ecosystem level) with longitudinal dimensions ranging from a few hundred meters to several kilometers, these tower fluxes need to be upscaled to regions, continents, or the globe. Therefore, future studies would focus on how to upscale fluxes of carbon, water, and energy from towers to broad regions by combining observation, modeling and remote sensing technique, and advance toward explicitly incorporating the impacts of climate change and human disturbance on ecosystem carbon exchange, examining the magnitude, distribution, and inter-annual variability of fluxes at regional to global scales, and quantifying uncertainties associated with gridded flux estimates.

Acknowledgments This study was supported by the National Science and technology support program of China (2012BAC19B04), the National Natural Science Foundation of China (grant no. 31170459 and no. 90711001), the Knowledge Innovation Program of the Chinese Academy of Sciences (KSCXZ-EW-J-29) and the research program “Climate Change: Carbon Budget and Relevant Issues” of Chinese Academy of Sciences (grant no. XDA05050402). We thank two anonymous reviewers for their valuable comments and suggestions on an earlier version of the manuscript. We also would like to thank Jianwu Tang for his help.

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