



# Is frequency or amount of precipitation more important in controlling CO<sub>2</sub> fluxes in the 30-year-old fenced and the moderately grazed temperate steppe?

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## ABSTRACT

Climate change is causing measurable change in rainfall patterns with uncertain implications for key processes in ecosystem function and carbon cycling. We conducted a modeling analysis to identify how variation in amount and frequency of precipitation affected on CO<sub>2</sub> fluxes and net primary productivity. The denitrification-decomposition model was used to quantify the effects of altered precipitation quantity and frequency under 12 climate scenarios over a period of 30-years on both a fenced and a moderately grazed temperate steppe in Inner Mongolia, China. The modeling results show the 12 climate scenarios had an obvious effect on gross primary productivity (GPP), ecosystem respiration ( $R_e$ ) and net primary productivity (NPP) in both a fenced and a grazed site. GPP,  $R_e$  and NPP increased in both sites under increased precipitation scenarios called A3 (+20% precipitation) and A4 (+40%) when compared with baseline conditions, while GPP,  $R_e$  and NPP declined under decreased precipitation scenarios A1 (-40% precipitation) and A2 (-20%) scenarios. The changed rainfall frequency resulted in a decline in GPP,  $R_e$  and NPP compared with those parameters under the base conditions at both sites. The ecologically effective rainfall ( $ER$ ), not total rainfall, controls the ecosystem CO<sub>2</sub> sink/source function. When  $ER$  exceeded 318 mm yr<sup>-1</sup> in the fenced site and 224 mm yr<sup>-1</sup> in the grazed site, the steppe switched from CO<sub>2</sub> emission to CO<sub>2</sub> absorption. CO<sub>2</sub> fluxes in the typical steppe which was fenced and moderately grazed are relatively responsive to changes in the amount of rainfall. However, in terms of the long-term modeling analysis, the modeled results suggest the effects of altered rainfall quantity, frequency and the interaction of rainfall quantity and frequency on CO<sub>2</sub> fluxes and plant productivity had no significant difference because of the fluctuating interannual biotic and abiotic factors.

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## 1. Introduction

Human activities have caused dramatic and unprecedented changes in the global chemical and physical environment, including increased atmospheric concentrations of CO<sub>2</sub>, other greenhouse gases, mean annual temperature and altered precipitation patterns (Trenberth, 1999; IPCC, 2007). Although climate change models differ with regard to projected future changes in annual precipitation amounts, they are in agreement in predicting that the dynamics and distribution of precipitation events will become more variable (Houghton et al., 2001). Substantial changes in precipitation

patterns and related moisture availability will undoubtedly affect ecosystems in arid and semiarid regions, where productivity is controlled by water availability (Weltzin et al., 2003). Grassland biomes cover a major portion of the earth's land surface (Bailey, 1998) and are important ecosystems for biological diversity and as resources for native and domestic grazers (Williams and Diebel, 1996). Seasonal, intra- and interannual water variability in rainfall both limits and drives patterns of biodiversity and productivity in these systems (Knapp et al., 2001).

The importance of the amount of precipitation vs. precipitation frequency in controlling net ecosystem carbon exchange (NEE, negative value means ecosystem uptake CO<sub>2</sub> from the atmosphere), ecosystem respiration ( $R_e$ ) and gross primary productivity (GPP), (NEE =  $R_e - GPP$ ) and net primary productivity (NPP, the difference between GPP and autotrophic respiration) in the grassland ecosystem have been assessed using short-term experimental rainfall

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manipulation plots in different grassland ecosystems (Fay et al., 2000; Knapp et al., 2002; Huxman et al., 2004; Nippert et al., 2006; Sherry et al., 2008; Miranda et al., 2009; Suseela et al., 2012) and these parameters have also been analyzed using a set of data derived from long-term observations and measurement in conjunction with records of precipitation history (Xiao et al., 1996; Knapp et al., 2006; Hao et al., 2010). Results of these research projects indicate C cycling in annual grasslands will be less sensitive to changes in rainfall quantity and more affected by altered timing of rainfall, and both precipitation amount and temporal pattern have been shown to be important in determining productivity.

Using long-term ecological data and historical precipitation records to identify how patterns of precipitation affect the ecological C cycling processes is an alternative approach to assessing potential changes in precipitation in grassland ecosystems. However, most of these methods used regression analysis, comparing the precipitation amount or coefficient of variation (CV) of precipitation against productivity to assess the responsiveness of productivity to interannual variations in precipitation. Subsequent experimental manipulation of precipitation events confirmed and defined this relationship (Knapp and Smith, 2001; Chou et al., 2008). However, these techniques face logical constraints and conceptual limitations including difficulties in determining the appropriate drop size, rainfall intensity, nutrient content, rates of infiltration and runoff as well as difficulties in determining the timing and magnitude of rainfall events (Weltzin et al., 2003). Also, rainfall manipulation experiments applied in different grassland ecosystems employed different methodology making it difficult to compare the results. The relationship of CO<sub>2</sub> fluxes and precipitation frequency is not well understood because of the lack of long-term experimental data (Wu et al., 2012).

Typical grassland areas in Inner Mongolia are important and representative parts of the Eurasian temperate grassland ecosystem. The part of the steppe that developed under semi-arid continental temperate climatic conditions is the largest grassland in China. Fenced and grazed management have been the main patterns for the recovery and use of this grassland ecosystem. The objective of this research was to identify the potential importance of variation in the amount and frequency of precipitation in controlling CO<sub>2</sub> fluxes and plant productivity over a 30-year-old study of both a fenced and moderately grazed steppe site based on biological and climatological data from 1978 to the present. To answer this question, we analyzed the relationships between long term natural precipitation and NPP and CO<sub>2</sub> fluxes simulated using the denitrification-decomposition (DNDC) model. Also, altered precipitation amounts and frequencies were used as input parameters to simulate CO<sub>2</sub> fluxes in a localized DNDC model. The modeled output and results were used to assess the influence of the variation in precipitation patterns on CO<sub>2</sub> fluxes in this steppe landscape. The specific aim was to evaluate the independent and interactive effects of increased/decreased rainfall amounts and an altered growing season rainfall pattern on CO<sub>2</sub> fluxes.

## 2. Materials and methods

### 2.1. Study site

Analyses were based on long-term ecological data collected at the experimental site located within the Inner Mongolia Grassland Ecosystem Research Station in the Xilin River watershed of the Inner Mongolia Autonomous Region (43°32'N, 116°40'E, 1200 m a.s.l.). The study site has been fenced against grazing since 1979 and is located on a smooth wide plain with low hills. The semi-arid continental temperate steppe climate is dry in spring and humid in summer. The average annual temperature is -0.5°C, with a growing

season of 150–180 d (May–September). The annual precipitation range is 320–400 mm, and rainfall is concentrated within the period from June to August.

The 86 species of flowering plants belong to 28 families and 67 genera growing at the site, including 11 grass species (Jiang, 1985). The xeric rhizomatous grass *Leymus chinensis* is the most dominant species, and *Agropyron cristatum*, *Cleistogenes squarrosa*, and *Carex duriuscula* are also dominant species. The heights of grass clusters are 50–60 cm; coverage averages 30–40% but can reach as high as 60–70% during rainy years. Litter accumulates within the enclosure because sheep are prevented from grazing in the area.

The grazed site where sheep were freely grazing during the normal season-long stocking rate during the growing season contains considerably fewer species of grasses than the fenced site, although *L. chinensis*, *Stipa grandis*, and *C. squarrosa* are the dominant species in both sites. *Artemisia frigida*, *Potentilla acaulis*, and *Chenopodium glaucum* comprise a large proportion of the total number of plants, but the biomass of these species only accounts for a small portion of the total biomass. The height of the grass clusters at the grazed site is 20–30 cm with coverage averaging 10–15% and almost no litter accumulation, because of sheep herding.

### 2.2. Data collection

At the *L. chinensis* steppe experimental site, field sampling began in early May and ended in mid-October, with sampling conducted at intervals of about two weeks since 1978. At each sampling date five 1-m<sup>2</sup> quadrats were randomly placed. Cover, density, growth height and phenological phases of each species were recorded. The above-ground parts of the quadrat's vegetation were clipped to ground level and immediately returned to the laboratory for wet- and later dry-matter measurements. The clipped plant material was separated into live and standing dead parts, which were weighed as the fresh weight of live biomass and standing dead biomass. Plant materials were oven-dried at 65 °C to a constant weight, and dry weights of live biomass and standing dead matter were recorded (Xiao et al., 1996). Litter from the sampled quadrates was also collected. The sum of all live above-ground biomass of individual species was used to calculate annual above-ground net primary productivity (ANPP) during the growing season (Xiao et al., 1996).

Two eddy covariance (EC) systems have been used to measure continuous CO<sub>2</sub> fluxes in the fenced site since 2003 and at the grazed sites since 2006 to validate the DNDC model. For a detailed description of the eddy covariance data processing and flux partitioning see Wang et al. (2011).

### 2.3. Models and simulation scenarios

A process-oriented biogeochemistry model, the DNDC model, was employed to analyze the relative importance of rainfall amount and frequency. Based on the encouraging results from the model validation tests and especially the modeled responses of NEE fluxes to the climate variation (Kang et al., 2011) the model was adapted to simulate the CO<sub>2</sub> fluxes from 1978 to 2007. The DNDC model was originally developed for predicting carbon sequestration and trace gas emissions from agroecosystems in the United States (Li et al., 1992a, 1992b, 1994). During the past decade, DNDC was further developed to include forest and grassland ecosystems and has since been expanded to simulate CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO and NH<sub>3</sub> emissions and the effects of global climate change (e.g., increased temperature and changed precipitation) (Li, 2000; Stange et al., 2000; Xu-Ri et al., 2003; Hsieh et al., 2005; Kesik et al., 2006; Kang et al., 2011). Using this model, the effect of climate change and environmental impacts such as increased temperature, changed precipitation pattern, land use type, human activities, and so on, on trace gas emissions can be comprehensively assessed.

DNDc consists of six sub-models for simulating soil climate, plant growth, soil organic matter decomposition, nitrification, denitrification and fermentation. The core of DNDc is a soil biogeochemical model describing carbon and nitrogen transport and transformation driven by a series of soil environmental factors, such as temperature, moisture, redox potential (i.e., Eh), pH and substrate concentration gradients, and anthropogenic activities including 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. Climate database (including air temperature and precipitation) have been built into DNDc and used as driving input data to simulate the soil water content and temperature profile at daily time steps, and then to predict the plant growth and soil organic matter decomposition. DNDc simulates plant growth driven by the air temperature, 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 thawing degree days. Daily water demand is calculated based on the daily N demand, daily potential biomass growth and water requirements. If there is not enough water or N to meet the demand, water stress or N stress will be modeled and will reduce the daily plant production. The daily increase in plant production will be modeled to be partitioned into the grain, shoot (leaf + stem) and root pools of the plant. The plant continuously assimilates atmospheric CO<sub>2</sub> into its biomass C and partitions products from CO<sub>2</sub> to the grain, leaves, stems and roots every day. When the plant reaches maturity or the temperature drops below 0 °C, senescence will begin. All the root litter will be incorporated into the soil profile; and the above-ground residue will be 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, called very labile litter, labile litter and resistant litter, on the basis of the C/N ratio of the litter. As the litter decomposes, part of the litter C is consumed as energy used by soil microbes which convert the litter to CO<sub>2</sub>. Part of the litter C is turned into microbial biomass. After the soil microbes die, the microbial remains will become humus and undergo further decomposition. During these sequential decomposition processes, part of the organic C becomes CO<sub>2</sub> and is emitted into the atmosphere. So, for the entire plant-soil-atmospheric system, if the CO<sub>2</sub> uptake rate is higher than the CO<sub>2</sub> emission rate, the ecosystem will gain C; otherwise, the ecosystem will become a source of atmospheric CO<sub>2</sub>.

In this study, a 30-year (1978–2007) daily weather dataset for the study site location was obtained from the climate database of our local meteorological station (the air temperature and precipitation during 2003–2007) and the Inner Mongolia Grassland Ecosystem Research Station, Chinese Academy of Sciences (the air temperature and precipitation during 1978–2002) and was utilized as inputs to simulate the 30-year grass growth and C dynamics. Twelve alternative climate scenarios were then composed by varying either the rainfall amount or frequency, or by modifying both the amount and frequency (Table 1). To distinguish the impacts of climate change, we assumed that all other input parameters, such as soil thermo-hydraulic properties and management practices, remained the same as in the validation tests across the climate scenarios. By running DNDc with the 30-year alternative climate scenario, we obtained annual grass yield and CO<sub>2</sub> flux components. The modeled grass productivity was compared with the long-term (1982–2007) observed NPP data for the location to further calibrate the DNDc model.

Moreover, as suggested by Smith et al. (1997), to quantify the discrepancy between the simulated and observed results, we adopted three statistical criteria for the validation tests: the

coefficient of determination ( $R^2$ , Eq. (1)), the root of mean square error (RMSE, Eq. (2)) and the relative mean deviation (RMD, Eq. (3)). Each criterion investigates a specific aspect of the correlation.

$$R^2 = \left( \frac{\sum(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum(O_i - \bar{O})^2 \sum(P_i - \bar{P})^2}} \right)^2 \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (2)$$

$$RMD = \frac{100}{\bar{O}} \sum_{i=1}^n \frac{|P_i - O_i|}{n} \quad (3)$$

where  $O_i$  and  $P_i$  represent the observed and model-predicted values, respectively.  $\bar{O}$  and  $\bar{P}$  are the mean of the observed and predicted values, respectively.  $n$  is the number of observations.

#### 2.4. Precipitation patterns index

Since we were interested in the question of how to quantify rainfall variability in a meaningful manner with ecosystem carbon fluxes in variable environments, analysis of the rainfall data involved characterizing long-term mean values, and calculation of indices of variability and trends in monthly, seasonal and annual time units. A modified Precipitation Shannon Index (PI), which reflects both the number of species and the relative abundance of these species, was applied from the species diversity literature (Anne and Colleen, 2006; Hao et al., 2010)

$$PI = \frac{-\sum p_i \ln(p_i)}{\ln(N)} \quad (4)$$

where  $p_i$  is the proportion of rainfall per month,  $N$  is the number of months = 12. A precipitation diversity index to one means each month had the same amount of rain (complete evenness) and an index equal to zero implies all rain fell in 1 month (complete unevenness).

Also, the coefficient of variation and the Precipitation Concentration Index (PCI) were used as statistical descriptors of rainfall variability. The PCI values were calculated as given by Oliver (1980);

$$PCI = 100 \times \left[ \frac{\sum Pt^2}{(\sum P_i)^2} \right] \quad (5)$$

where  $\sum$  = summation over the 12 months. According to Oliver (1980), PCI values of less than 10 indicate a uniform monthly distribution of rainfall, values between 11 and 20 indicate high concentration, and values of 21 and above indicate a very high concentration of rainfall in one or a few months.

#### 2.5. Data analysis

Statistical analyses were performed using ANOVA models in SAS 9.2 (Institute Inc., Cary, NC, USA) to compare the CO<sub>2</sub> fluxes and NPP simulated by the DNDc model. Before conducting a two-way classification of nested ANOVA, the normality of error terms was evaluated using the Kolmogorov-Smirnov test for goodness of fit, and homoscedasticity was evaluated with the Levene's test for equality of variances. The alternative climate treatments (amount, control and frequency) and scenarios in treatments (increase/decrease amount, frequency and their interaction) were treated as independent variables, and CO<sub>2</sub> fluxes and NPP as the dependent variable separately. When treatment effects or scenarios were significantly different, Duncan's Multiple Range Test was used to compare the mean values among the treatments ( $P < 0.05$ ).

**Table 1**

Alternative climate scenarios during growing season for predicting impacts of climate change on C dynamics in the grassland in Inner Mongolia, China.

Change in amount of precipitation	Change in frequency of precipitation				
	60% A1F1	80%	100% A1	120% A2	140% A1F4
60%					
80%					
100%	F1				
120%		F2			
140%			Base		
	A4F1			F3	
				A4	
					A4F4

A1 Decrease in amount of precipitation by 40%, A2 decrease amount of precipitation by 20%, A3 increase amount of precipitation by 20%, A4 increase amount of precipitation by 40%, F1 decrease in frequency of precipitation by 40%, F2 decrease in frequency of precipitation by 20%, F3 increase in frequency of precipitation by 20%, F4 increase in frequency of precipitation by 40%, A1F1 decrease in amount of precipitation by 40% while decrease in frequency of precipitation by 40%, A1F4 decrease in amount of precipitation by 40% while increase in frequency of precipitation by 40%, A4F1 increase in amount of precipitation by 40% while decrease in frequency of precipitation by 40%, A4F4 increase in amount of precipitation by 40% while increase in frequency of precipitation by 40%.

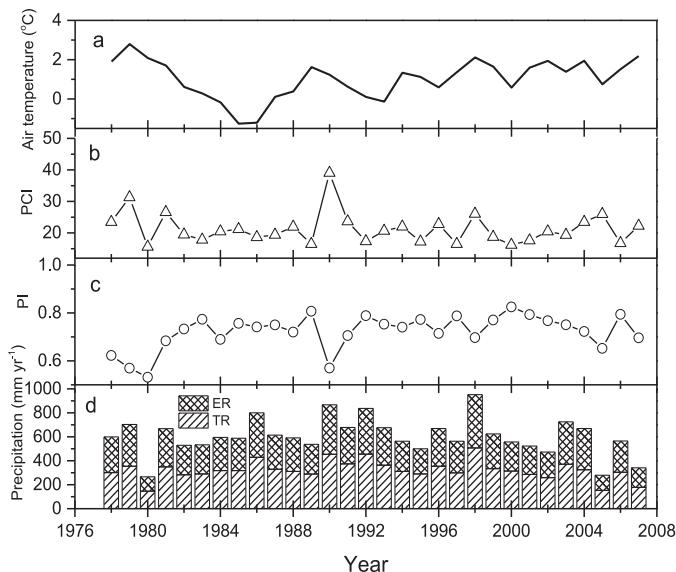
### 3. Results

#### 3.1. Precipitation patterns

Average annual temperature ranged from 2.7 °C in 1979 to –1.3 °C in 1985, with an average value of 1.0 °C and the coefficient of variation (CV) of 96% (Fig. 1a). Annual total precipitation (TR) varied from 145.7 mm yr<sup>−1</sup> in 1980 to 507.0 mm yr<sup>−1</sup> in 1998, with a mean of 321.6 mm yr<sup>−1</sup> (Fig. 1d). On average, 87% of annual precipitation in the study period fell in April–September. The CV in annual precipitation was 25%. This indicated precipitation exhibits large inter-annual fluctuations in typical steppe habitat. The ecological effective precipitation (>5 mm d<sup>−1</sup> rainfall, ER) varied from 120.4 mm yr<sup>−1</sup> in 1980 to 445.7 mm yr<sup>−1</sup> in 1998, with a mean of 281.2 mm yr<sup>−1</sup>. The averaged ER accounted for 88% of total rainfall. The calculated PI and PCI shows that rainfall in this region is generally characterized by high to very high monthly concentration; PCI values ranged from 21% in 1989 to 47% in 1990 and PI values ranged from 0.53 in 1980 to 0.82 in 2000 (Fig. 1b and c).

#### 3.2. Model validation and results under climate

Seasonal patterns of CO<sub>2</sub> fluxes from this ecosystem for the observed and DNDC modeled outputs were validated by Kang et al. (2011). To test the applicability of DNDC for long-term NPP simulation, we used the long-term (1982–2007) observed NPP data

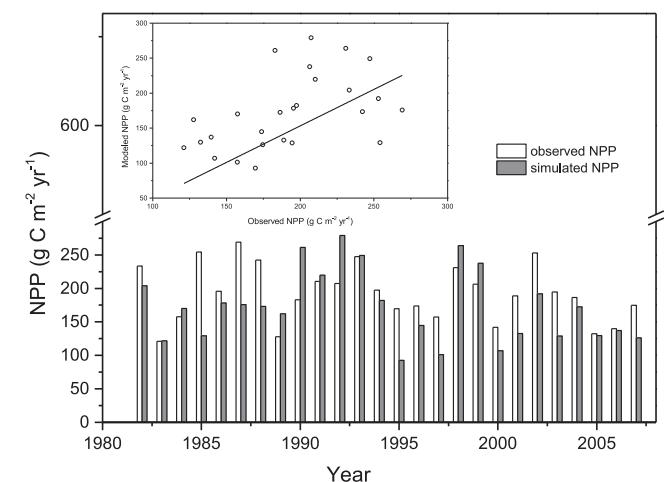


**Fig. 1.** Annual mean air atmosphere temperature (a), the coefficient of variation (CV) and the precipitation concentration index (PCI) (b), precipitation Shannon index (PI) (c), the annual total amount of rainfall (TR) and ecologically effective rainfall (ER) (d) from 1978 to 2007 over a typical steppe in Inner Mongolia Plateau, China.

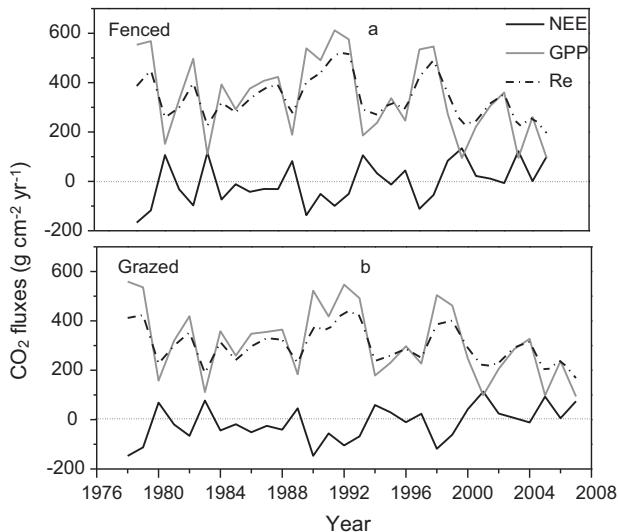
for the location to further calibrate the DNDC model. The modeled magnitudes of NPP were basically in agreement with observations (Fig. 2). On an annual basis, the measured NPP were ranged from 269.2 to 121.2 g C m<sup>−2</sup> yr<sup>−1</sup>, and the modeled NPP were from 279.1 to 92.6 g C m<sup>−2</sup> yr<sup>−1</sup>. The correlation between the measured and modeled annual NPP was expressed with the R-squared values as 0.32 ( $P < 0.01$ ). The values of RMSE and RMD were 25.9% and –8.5%, respectively. In general, by comparing the modeled results with observations at short-term and long-term temporal scales, we gained confidence about the applicability of DNDC for this grassland ecosystem.

The ecosystem CO<sub>2</sub> fluxes showed a large inter-annual fluctuation from 1978 to 2007 at both sites, and broadly tracked the temporal variability in the amount of precipitation. The temporal dynamics of ecosystem CO<sub>2</sub> fluxes from 1978 to 2007 showed rainfall (TR and ER) usually increased CO<sub>2</sub> fixation, and extended dry intervals typically decreased CO<sub>2</sub> uptake. The maximum and minimum GPP were 611.8 g C m<sup>−2</sup> yr<sup>−1</sup> in 1992 with 455 mm TR and 381.9 ER, and 95.1 g C m<sup>−2</sup> yr<sup>−1</sup> in 2007 with 177.8 mm TR and 163.5 mm ER, respectively, in the fenced site. There was no distinction between the overall response pattern of modeled  $R_e$  and GPP (Fig. 3a). However, the magnitude of  $R_e$  responses was somewhat smaller than that for the GPP responses. The values ranged from a maximum of 524.7 g C m<sup>−2</sup> yr<sup>−1</sup> in 1993 with 312.8 mm TR and 289.2 mm ER to a minimum of 195.9 g C m<sup>−2</sup> yr<sup>−1</sup> in 2007 with 163.5 mm TR and 132.5 mm ER. The maximum of GPP and  $R_e$  coincided temporally except for the maximum values where  $R_e$  lagged behind GPP (Fig. 3a).

At the grazed site, modeled CO<sub>2</sub> fluxes in the normal scenario were different from those of the fenced site. The maximum



**Fig. 2.** Comparisons between simulated and observed net primary productivity (NPP), and simulated vs. observed annual NPP (top panel,  $R^2 = 0.32$ ,  $P < 0.01$ ) for the fenced site of the Inner Mongolia grassland, using data from 1982 to 2007.



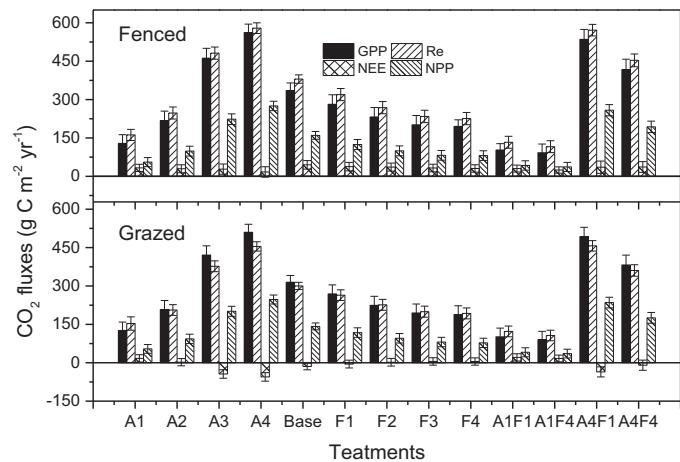
**Fig. 3.** Modeled annual variation in net ecosystem exchange (NEE), ecosystem respiration ( $R_e$ ) and gross primary productivity (GPP) using DNDC model from 1978 to 2007 in a fenced grassland and a grazed grassland in Inner Mongolia Plateau.

and minimum values of GPP and  $R_e$  were less than those in the fenced site. GPP and  $R_e$  ranged from  $93.7 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 2007 to  $559.2 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 1978, and from  $168.1 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 2007 to  $442.6 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 1992, respectively (Fig. 3b). Both sites exhibited the maximum CO<sub>2</sub> uptake in 1978, and released the maximum CO<sub>2</sub> in 2001. The maximum CO<sub>2</sub> uptake and emissions were 150.4 and 200.6, and 147.2 and  $143.2 \text{ g C m}^{-2} \text{ yr}^{-1}$  in the fenced and grazed sites, respectively.

At both study sites, modeled GPP was stimulated by increased precipitation (A3: +20% and A4: +40% scenarios), depressed by reduced precipitation (A1: -40% and A2: -20%) and frequency variability scenarios (F1-F4 scenarios: -40%, -20%, +20% and +40% precipitation events). Interactive effects of the amount of precipitation and frequency change on GPP were different in each scenario. Based only on treatments with an increase amount of precipitation, the interaction between the amount of precipitation and variability in its frequency had a positive effect on GPP (Fig. 4). The overall response pattern of modeled  $R_e$  to the treatments was similar to that of GPP (Fig. 4). However, the magnitude of the response of  $R_e$  was different for both study sites. In the fenced site, the scale of the  $R_e$  response was somewhat higher than that of the GPP responses. Specifically, modeled  $R_e$  increased when the amount of precipitation increased but decreased with less rainfall and a change in precipitation frequency.

### 3.3. The variation in CO<sub>2</sub> source and sink

Modeled NEE in both sites was significantly different under different climate scenarios. In the fenced site, the ecosystem acted as a CO<sub>2</sub> source no matter how the amount or frequency of precipitation changed separately or when combined. But in the grazed site, this ecosystem absorbed CO<sub>2</sub> from the atmosphere under both increased rainfall treatments and when the frequency changed based on the +40% rainfall treatment (Fig. 4). When compared to the control or baseline conditions, modeled NPP increase by approximately 40% and 72% under the A3 and A4 increased rainfall treatments, respectively, and declined by 22% and 77% under the A2 and A1 decreased precipitation patterns, respectively. The interactive effects of changing the precipitation amount and rainfall frequency on NPP were positive for all sites with increased rainfall while they were negative with decreased rainfall amounts (Fig. 4).

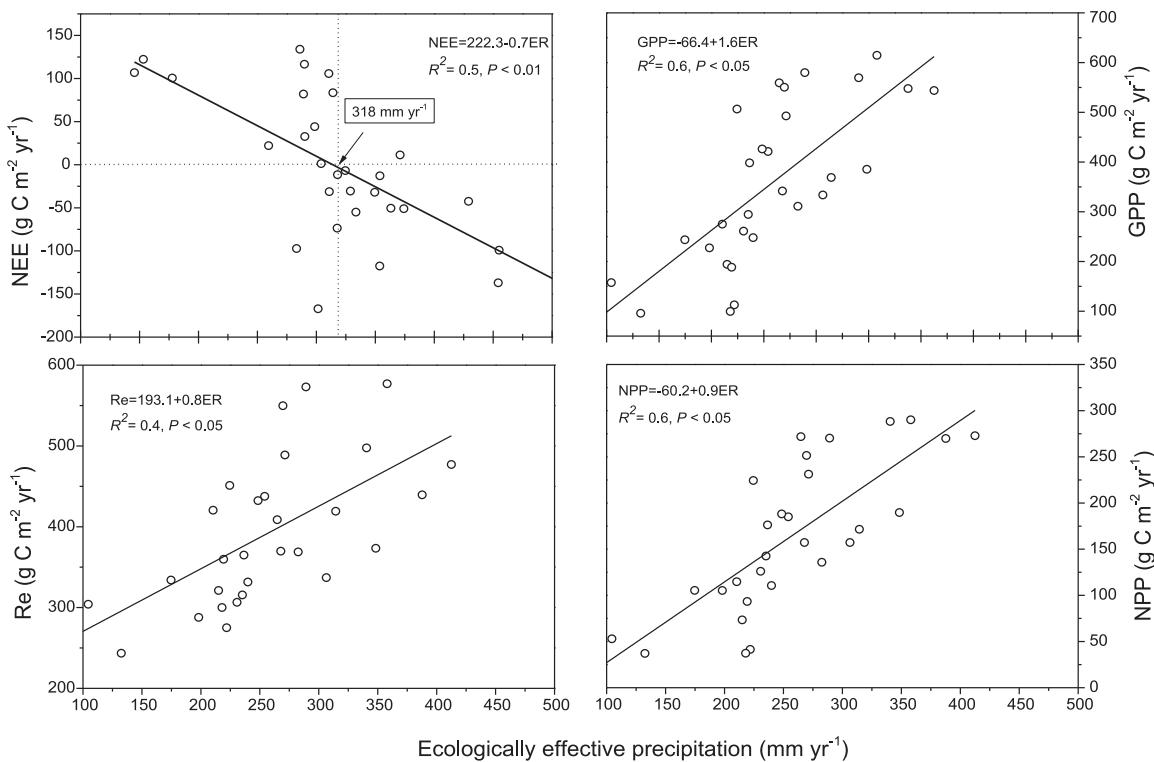


**Fig. 4.** Difference ( $\text{g C m}^{-2} \text{ yr}^{-1}$ ) in simulated net ecosystem CO<sub>2</sub> exchange (NEE), ecosystem respiration (Re), gross primary productivity (GPP) and net primary productivity (NPP) in response to scenarios in treatment of decrease in amount of precipitation by 40% (A1), decrease amount of precipitation by 20% (A2), increase amount of precipitation by 20% (A3), increase amount of precipitation by 40% (A4), decrease in frequency of precipitation by 40% (F1), decrease in frequency of precipitation by 20% (F2), increase in frequency of precipitation by 20% (F4), and their interactive from 1978 to 2007 in a fenced grassland and a grazed grassland in Inner Mongolia Plateau (mean  $\pm$  standard error).

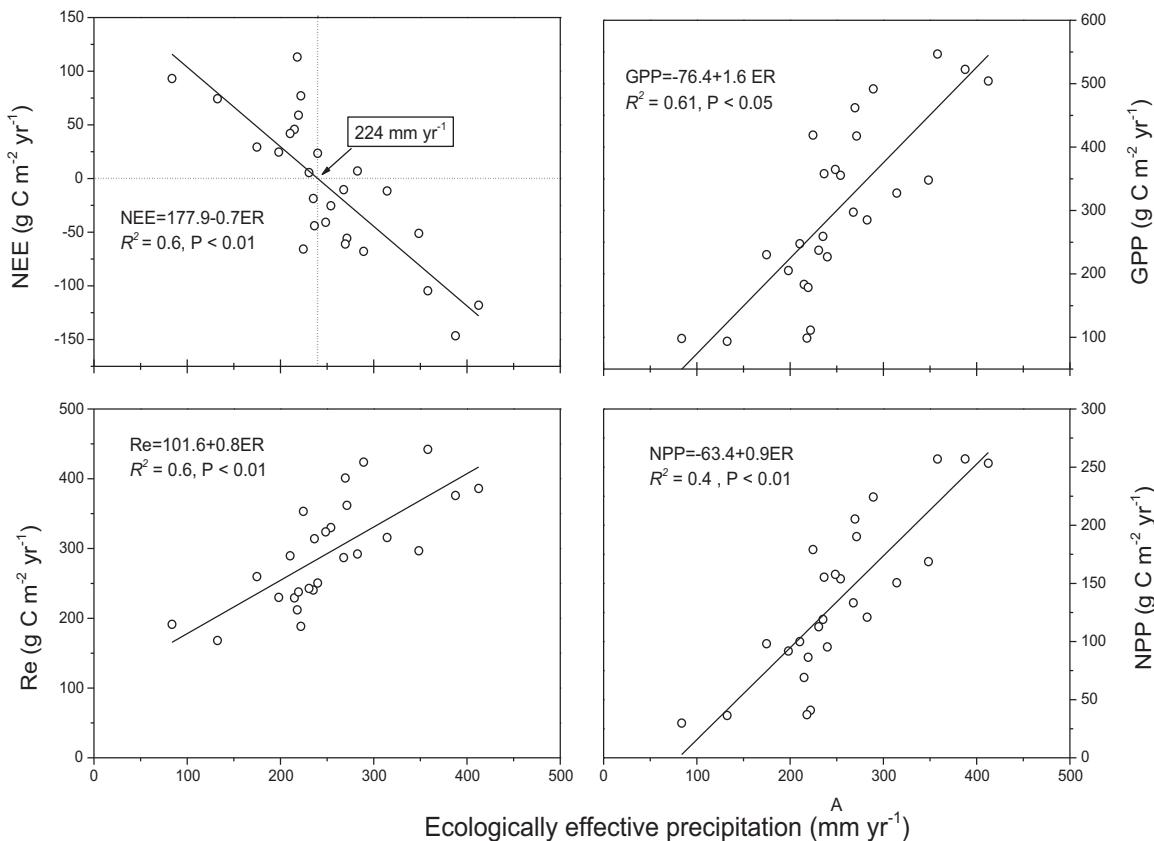
## 4. Discussion

### 4.1. The relationship between CO<sub>2</sub> fluxes and the amount of precipitation

Potential changes in both the amounts and frequency of precipitation events are vital aspects of regional climate change, which can alter the distribution and dynamics of water availability and subsequently alter biological processes at the ecosystem level. The total amount of precipitation and soil water content associated with rainfall play the most prominent role in grassland through their influence on plant productivity (Sala and Lauenroth, 1982; Xiao et al., 1996) and soil carbon cycle processes (Epstein et al., 1997; Harper et al., 2005). Most of the literature indicates that there is a positive correlation between productivity and annual total amount of rainfall (Nippert et al., 2006). However, our results showed that ecologically effective rainfall (ER) which refers to a rainfall event altering soil and plant water status and resulting in a discernible variation of ecosystem-atmospheric CO<sub>2</sub> fluxes (Hao et al., 2010, 2012), not total rainfall, control the ecosystem CO<sub>2</sub> fluxes and plant dynamics. Net ecosystem exchange was significantly negatively correlated with ER at both two study sites ( $R^2 = 0.5$  in the fenced site and  $R^2 = 0.6$  in the grazed site, Figs. 5 and 6). In contrast, ecologically effective rainfall was positively correlated to GPP,  $R_e$  and NPP in both sites. One possible reason CO<sub>2</sub> fluxes were more strongly correlated with ER than with the total amount of precipitation was the triggering response of the physiological activity of vegetation to a 5 mm rainfall event might have an important effect on the carbon cycle in the steppe region (Hao et al., 2010, 2012). When ER exceeded  $318 \text{ mm yr}^{-1}$  in the fenced site and  $224 \text{ mm yr}^{-1}$  in the grazed site, the steppe switched from CO<sub>2</sub> emission to CO<sub>2</sub> absorption. This implies that the variation in precipitation frequency had a little effect on this steppe as a CO<sub>2</sub> sink so long as the ER did exceed a given threshold in natural conditions. The higher ER threshold measured at the fenced site than at the grazed site can be attributed to higher levels of precipitation interception associated with the higher levels of litter accumulation and leaf area index at the fenced site (Wang et al., 2011).



**Fig. 5.** The relationship between modeled net ecosystem CO<sub>2</sub> exchange (NEE), ecosystem respiration ( $R_e$ ), gross primary productivity (GPP), net primary productivity (NPP) and observed ecologically effective ecological rainfall (ER) in a fenced steppe.



**Fig. 6.** The relationship between modeled net ecosystem CO<sub>2</sub> exchange (NEE), ecosystem respiration ( $R_e$ ), gross primary productivity (GPP), net primary productivity (NPP) and observed ecologically effective ecological rainfall (ER) in a grazed steppe.

**Table 2**

The Statistical Analysis on the GPP, NEE,  $R_e$  and NPP simulated by the DNDC model over a 30-year fenced and grazed grassland in Inner Mongolia plateau.

Land use type	Variable	Factors	DF	F value	P
Fenced	GPP	Treatment	3	0.32	0.81
		Scenarios in treatment	9	91.97	<0.0001
		Year	29	38.13	<0.0001
	NEE	Treatment	3	2.81	0.09
		Scenarios in treatment	9	0.30	0.97
		Year	29	21.68	<0.0001
	$R_e$	Treatment	3	1.08	0.41
		Scenarios in treatment	9	212.73	<0.0001
		Year	29	4.14	<0.0001
	NPP	Treatment	3	0.41	0.75
		Scenarios in treatment	9	82.05	<0.0001
		Year	29	38.34	<0.001
Grazed	GPP	Treatment	3	0.28	0.83
		Scenarios in treatment	9	91.04	<0.0001
		Year	29	43.99	<0.0001
	NEE	Treatment	3	0.57	0.65
		Scenarios in treatment	9	7.23	<0.0001
		Year	29	22.98	<0.0001
	$R_e$	Treatment	3	0.26	0.85
		Scenarios in treatment	9	183.3	<0.0001
		Year	29	49.10	<0.0001
	NPP	Treatment	3	0.36	0.78
		Scenarios in treatment	9	79.98	<0.0001
		Year	29	43.89	<0.0001

#### 4.2. The effect of changing precipitation patterns on $\text{CO}_2$ fluxes

Precipitation variability, including quantity and timing of rainfall, is still a very important issue in terrestrial ecosystem research. It is well known that precipitation quantity influences grassland net primary productivity positively (*NPP*), net ecosystem exchange (*NEE*) and its components (Alward et al., 1999; Rastetter et al., 2003; Dune et al., 2004; Nippert et al., 2006), whereas experimental increases in terms of temporal variability in water availability commonly exhibits a negative relationship with *NPP* and *NEE* (Fay et al., 2008; Huxman et al., 2004; Chou et al., 2008; Heisler-white et al., 2008). Our modeled results indicated there was no significant difference in the effects of the four treatments (quantity, frequency, control and quantity  $\times$  frequency) on *GPP*,  $R_e$ , *NEE* and *NPP* at both study sites (Table 2). In contrast, there was a significant effect of various scenarios within treatments on *GPP*,  $R_e$  and *NPP* at both sites. However, the influence of scenarios within treatments on *NEE* was not obviously different at the fenced site ( $F=0.30$ ,  $P=0.97$ ) while it was significant at the grazed site ( $F=7.23$ ,  $P<0.0001$ ). The response of *GPP* and  $R_e$  to precipitation variability is different and the response of *NEE* and its components to precipitation patterns is more sensitive in the grazed site than the fenced steppe (Wang et al., 2011). *GPP*,  $R_e$ , *NEE* and *NPP* had significant interannual differences at both sites (Table 2).

The results derived from the manipulative experiments conducted over a 2–6 year period suggested the C cycle will be less sensitive to changes in rainfall quantity and more affected by altered seasonal timing of rainfall, and will result in significant C losses in the grassland ecosystems (Fay et al., 2000; Harper et al., 2005; Chou et al., 2008; Juan De Dios et al., 2009). Short-term experimental manipulations of water availability excluded the effects of the other vital environment factors (such as shifts in temperature, wind and radiation, etc.) imposed by rainfall exclusion shelters and did not consider fluctuating interannual changes of biotic and abiotic factors (Weltzin et al., 2003). The variation in water availability had a delayed effect on the C cycle; the effect can last for less than a year or perhaps up to 7 years, with one year being the most commonly reported time period (Nippert et al., 2006; Sherry et al., 2008). Temporal changes in the limitation of the C cycle are buffered by storage of accumulated carbohydrates during times

when water availability is high and plants use their stores to counteract  $\text{CO}_2$  losses when the water supply declines (Chapin et al., 1990). Also, the “compensatory effect” in this fenced mature steppe ecosystems with high biodiversity and ecosystem stability reduced variability in ecosystem productivity in that one species increases its abundance in response to the reduction of another species in a fluctuating environment (Bai et al., 2004). This moderately grazed site with more leaves with greater leaf-level photosynthetic capacity, open canopy architecture with greater radiation use efficiency, and reduced canopy respiration compensated for the lower leaf area at the grazed site, can counterbalance the effect the environment fluctuation (Wang et al., 2011). Therefore, the effect of the four treatments on  $\text{CO}_2$  fluxes in both study sites was not significantly different in terms of the long-term modeled results (Table 2).

Wu et al. (2012) suggested precipitation frequencies were better indicators of the soil water content (SWC) during the growing season than precipitation totals, and frequencies may play an important role in regulating both interannual and spatial variations of SWC; this fact has probably been overlooked or underestimated. The modeled results using four well-established process-based ecosystem models (LPJ, DayCent, ORCHIDEE, TECO) in seven terrestrial ecosystems with distinctive vegetation types in different hydro-climatic zones indicated that the effect of halved rainfall frequency on *NPP* was mostly negligible. Doubled rainfall frequency induced somewhat more pronounced changes at seasonally dry sites (Gerten et al., 2008). However, we concluded the change in rainfall frequency resulted in a decline in *GPP*,  $R_e$  and *NPP* compared with those under base condition at both sites. A decrease in rainfall frequency based on an unchanged rainfall total results in a longer interval between rainfall events ( $I$ ) and larger single rainfall size, and vice versa. The magnitude and direction of response to variation in  $I$  depended on several factors, including the threshold event size for the ecosystem process (Reynolds et al., 2004; Hao et al., 2011), total rainfall (Swemmer et al., 2007), fluctuating intra- and interannual abiotic disturbance (Fay et al., 2008) and species composition and life stage (Swemmer et al., 2007). Also, previous patterns in precipitation and soil moisture may either promote or suppress the response of ecosystem processes, which results in differential responses among key ecosystem processes controlling C cycling (Potts et al., 2006; Nippert et al., 2006). At the same time,

**Table 3**

The standardized estimated for ecologically effective rainfall (*ER*), Precipitation Shannon index (*PI*) and the multiple liner regression equations under the Base scenario. *GPP*, *NEE*, *R<sub>e</sub>* and *NPP* units: g C m<sup>-2</sup> yr<sup>-1</sup>.

	Variables	Standardized estimated ER	Standardized estimated PI	Equation	R <sup>2</sup>	P
Fenced	GPP	0.75	-0.18	$GPP = 22.4 + 1.6ER - 396.1PI$	0.60	<0.0001
	NEE	-0.70	0.31	$NEE = -26.2 - 0.85ER + 388.6PI$	0.61	<0.001
	R <sub>e</sub>	0.64	-0.01	$R_e = 198.5 + 0.77ER - 7.46PI$	0.42	<0.05
	NPP	0.78	-0.20	$NPP = 102.8 + 0.86ER - 221.8PI$	0.67	<0.001
Grazed	GPP	0.76	-0.24	$GPP = 294.5 + 1.5ER - 482.3PI$	0.65	<0.0001
	NEE	-0.79	0.19	$NEE = -41.7 - 0.7ER + 288.6PI$	0.70	<0.0001
	R <sub>e</sub>	0.72	-0.18	$R_e = 252.8 + 0.7ER - 193.7PI$	0.50	<0.0001
	NPP	0.79	-0.25	$NPP = 135.6 + 0.8ER - 262.PI$	0.71	<0.0001

a multiple regression model combining precipitation amount and frequency distribution was applied to evaluate their relative importance on CO<sub>2</sub> fluxes. These results also suggest the effect of altered rainfall frequency on *GPP*, *R<sub>e</sub>*, *NEE* and *NPP* were much weaker than those induced by altered rainfall amounts (Table 3).

Under the A4F1 and A4F4 scenarios, simulated interactive effects of precipitation quantity and frequency on *GPP*, *NEE*, *R<sub>e</sub>* and *NPP* were consistent with those under the A3 and A4 scenarios. The positive interactions of increased rainfall amount scenarios with rainfall frequency patterns apparently resulted from various mechanisms including those mentioned above. The plant physiological mechanisms and ecological processes induced by increased rainfall amounts minimized the negative effects of long or short term soil drying and alleviated water stress under the variation in rainfall frequency (Fay et al., 2008). Thus, the responses of C cycling to a given the rainfall frequency with individual events varied greatly depending on the annual precipitation quantity.

#### 4.3. The importance of climate-change impacts on grassland function

The structure of ecosystem biogeochemical models is reasonably strong and built upon well-established experimental evidence indicating fluxes of carbon, nutrients, and water among compartments are largely donor pool-controlled (Luo and Reynolds, 1999; Luo et al., 2008). However, these models do not take into account the variations in plant composition. As illustrated by Weltzin et al. (2003) a new generation of models called dynamic global vegetation models integrate the objectives of vegetation and ecosystem modeling and are capable of simulating transient and long-term effects of interannual variation in precipitation on CO<sub>2</sub> cycle. Thus, it is crucial to improve various mechanistic response functions including vegetation dynamics for this model.

## 5. Conclusions

This modeling analysis illustrated CO<sub>2</sub> fluxes and plant productivity differed in their response to changes in rainfall regimes in two different managed grasslands. *NPP* increased with increasing amounts of precipitation in two sites. CO<sub>2</sub> fluxes, however, were more sensitive to rain quantity than to the frequency of rainfall. The ecologically effective rainfall (*ER*), not total rainfall, controls the ecosystem CO<sub>2</sub> sink/source function. When *ER* exceeded 318 mm yr<sup>-1</sup> in the fenced site and 224 mm yr<sup>-1</sup> in the grazed site, the steppe switched from CO<sub>2</sub> emission to CO<sub>2</sub> absorption. Our modeling analysis suggests CO<sub>2</sub> fluxes in the typical steppe with fenced and moderate grazing management is relatively responsive to changes in the amount of rainfall.

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