Agricultural and Forest Meteorology 178–179 (2013) 46–55

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Precipitation amount, seasonality and frequency regulate carbon cycling of a semi-arid grassland ecosystem in Inner Mongolia, China: A modeling analysis

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ARTICLE INFO

Article history:
Received 16 August 2012
Received in revised form 30 January 2013
Accepted 4 February 2013

Keywords:
Precipitation amount
Precipitation seasonality
Precipitation frequency
Grassland
Net primary production
Net ecosystem production
Heterotrophic respiration

ABSTRACT

Over the last century, precipitation has shown significant changes, reflecting both natural variability and radiative forcing changes from greenhouse gases and aerosols. Arid and semi-arid ecosystems are particularly sensitive to changes in precipitation regimes. In this study, we investigate how variation in annual total, seasonal distribution and frequency of precipitation affect CO_2 fluxes of semi-arid grassland in Inner Mongolia. To this aim, we combine eddy-covariance measurements with a process-based model (ORCHIDEE). First, the ORCHIDEE parameters were optimized using half-hourly CO_2 flux data and actual precipitation forcing. Second, the response of CO_2 fluxes to altered precipitation scenarios is computed using the model with optimized parameters. Our results show that modeled net primary production (NPP) responds non-linearly to increased vs. decreased rainfall. Re-allocating precipitation from other seasons to spring enhances annual NPP and net ecosystem production (NEP). By contrast, re-allocating more precipitation to autumn was found to decrease annual NPP and NEP. Increasing the frequency of heavy rainfall days ($PF_{10\,mm}$, days with precipitation more than 10 mm) induces a positive response of simulated NPP during the growing season. However, the increase of the frequency of moderately rainy days ($PF_{5\text{–}10\,mm}$, days with precipitation between 5 mm and 10 mm) rather increases soil heterotrophic respiration. Taken together, our modeling results are consistent with that of grassland field manipulation experiments. This study highlights the importance of changes in precipitation seasonality and frequency for semi-arid grassland. Further investigations should focus on testing the ability of models to reproduced manipulation experiment data, and on evaluating the performances of climate models to reproduce rainfall intensity/frequency in semi-arid areas.

1. Introduction

An amplification of the hydrological cycle has been observed along with increasing temperature during the past several decades (IPCC, 2007). This human induced alteration of the hydrological cycle superimposed on a large natural variability may result in altered regional precipitation amount, frequency, intensity, duration and extremes (Easterling et al., 2000; Trenberth et al., 2003; IPCC, 2007). Over the 20th century, possible change in annual precipitation amount and an intensification of inter- and intra-annual variability of precipitation were reported (Easterling et al., 2000; IPCC, 2007). Precipitation appears to shift toward fewer and larger rainfall events (Tank and Konnen, 2003; Trenberth et al., 2003). For example, East Asia has experienced a significant decrease of precipitation frequency, and a significant change of precipitation seasonality. Autumn precipitation decreased while winter precipitation increased, from 1960 to 2006 (Ding et al., 2007; Piao et al., 2010). The change in soil moisture induced by these precipitation regime changes in water-limited ecosystems impact carbon cycling processes such as net primary production (NPP), heterotrophic respiration (Rh) and the sum of both, net ecosystem production (NEP) (Knapp and Smith, 2001; Knapp et al., 2002; Gerten et al., 2008; Luo et al., 2008; Robertson et al., 2009; Fay, 2009; Ross et al., 2012). Climate models projections predict significant changes in precipitation amount, timing and frequency for the next 50 years (IPCC,

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http://dx.doi.org/10.1016/j.agrformet.2013.02.002

2007; Wentz et al., 2007; Gao et al., 2008), which will continue to influence productivity and carbon sequestration of terrestrial ecosystems (Luo et al., 2008; Knapp et al., 2008). Therefore, it is essential to understand how changes in precipitation regimes impacts carbon cycling processes in terrestrial ecosystems using observations and ecosystem models, especially for water-limited ecosystems that directly and strongly respond to precipitation changes.

In water-limited ecosystems, many studies found a significant and positive correlation between inter-annual variation of precipitation amount and NPP from site level studies (e.g. Churkina et al., 1999; Knapp and Smith, 2001; Huxman et al., 2004). However, variability in the seasonality and frequency of precipitation events, as well as co-variability of other climate drivers with precipitation, could lead to confounding effects when investigating the response of ecosystem processes to annual precipitation changes using real-world conditions (Huxman et al., 2004; Fay, 2009; Wu et al., 2011). On the other hand, ecosystem manipulation experiments (under controlled climate conditions) and ecosystem model simulations of precipitation addition and reduction have shown that higher precipitation amount leads to larger NPP, when keeping other confounding variables (e.g. precipitation seasonality, precipitation frequency and temperature) constant (Zavaleta et al., 2003; Dukes et al., 2005; Chou et al., 2008; Gerten et al., 2008; Luo et al., 2008). Hence, the first goal of this study is to investigate, using a process-based ecosystem model prescribed with high frequency climate forcing data, how changes in precipitation amount change the carbon fluxes of a semi-arid grassland ecosystem while keeping precipitation timing and other confounding variables constant.

The impacts of precipitation on NPP are different between the growing season and the non-growing season, in particular for grassland ecosystems (Robertson et al., 2009). Precipitation during the growing season directly and positively impact vegetation NPP in semi-arid grasslands, whereas precipitation outside the growing season only have an indirect lagged effect through soil moisture (Muldavin et al., 2008; Robertson et al., 2009). Thus, the second goal of this study is to investigate how changes in the seasonal distribution of precipitation influence carbon fluxes in a semi-arid grassland ecosystem.

Variations in precipitation intensity and frequency are receiving more and more attention for their effect in controlling semi-arid grassland ecosystem processes (Knapp et al., 2002, 2008; Robertson et al., 2009; Fay, 2009). A different precipitation frequency is likely to modify soil moisture, which will in turn influence NPP, respiration and the net carbon balance of the ecosystem (Knapp et al., 2002, 2008). A decrease in precipitation frequency accompanied by an increase in precipitation intensity per rainfall event, as projected from climate models, could amplify the magnitude of the soil moisture fluctuations, and lengthen the period of water stress in-between two consecutive rainfall events (Knapp et al., 2002, 2008). On the other hand, larger (more extreme) rainfall events could also more efficiently replenish deep soil moisture in xeric ecosystems (Knapp et al., 2008) and cause an increase in NPP. Thus, research results on the impacts of intra-annual variations of precipitation distribution on ecosystem processes are still inconclusive (Knapp et al., 2008; Fay, 2009; Ross et al., 2012). Until now, only a few studies including ecosystem manipulation experiments, remote sensing and model simulations explored the effects of altered precipitation frequency on ecosystem processes (e.g. Fang et al., 2005; Luo et al., 2008; Wu et al., 2011). Thus, the third aim of this study is to simulate with a process-based ecosystem model how variation of number of daily precipitation events influences carbon cycling processes of a semi-arid grassland ecosystem in China while maintaining annual total precipitation amount constant.

We constructed different altered precipitation input data for the model, in order to separate the influence of changes in precipitation annual amount, seasonal distribution, and daily frequency on carbon fluxes at the Chinese semi-arid grassland ecosystem site investigated. Before applying this altered precipitation forcing to the model, we optimized its parameters against one year carbon flux measurements, in order to ensure that the observed response of carbon fluxes to real-world precipitation is correctly reproduced. We address the following three questions for a semi-arid grassland ecosystem site, representative of Inner Asia semi-arid grasslands.

(1) How does a change in annual precipitation modify ecosystem carbon fluxes when keeping precipitation timing and frequency constant?
(2) How does a change in precipitation seasonality modify ecosystem carbon fluxes when keeping total precipitation amount and frequency constant?
(3) How does an altered precipitation frequency modify ecosystem carbon fluxes when keeping total precipitation amount constant?

2. Materials and methods

2.1. Study site

Simulation experiments with altered precipitation were conducted at a grassland site (N43°33′16″, E116°40′17″) equipped with an eddy flux tower (CN-Xi2) in Xilinhot, Inner Mongolia, China. This site, 1250 m above sea level, has a temperate continental climate with mean annual precipitation of 342 mm (average during the period of 1980–2009). Driven by Asian monsoon, a large portion of annual precipitation (87%) occurs from May to September. Mean annual temperature is 1.2 °C (long term), while monthly mean temperature is 19.0 °C in July and −19.2 °C in January (Fig. 1). Soils in this site are Chestnut series (Yuan et al., 2005). Soil texture is comprised by ~58% sand, ~27% silt and ~15% clay, respectively. Vegetation basal cover ranges from 30% to 45% and is mainly comprised of C_3 species with dominant species of *Stipa grandis* and *Artemisia frigida*, and the biomass of *Stipa grandis* is about 70–90% (Li et al., 2008). Half-hour eddy flux data in the year 2006 is from the global fluxnet (http://www.fluxdata.org/), and detailed gap-filling and uncertainty of flux data in this site are given in Zhang et al. (2011). The chosen site for this study is a typical semi-arid grassland ecosystem and could represent the large area of semi-arid grassland in Inner Asia (Zhang et al., 2011).

2.2. ORCHIDEE model

In this study we used ORCHIDEE, a process-based land-surface model (Krinner et al., 2005), to simulate how carbon fluxes respond

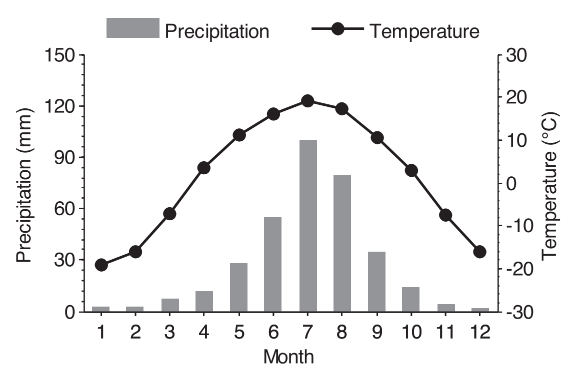

Fig. 1. Seasonal cycle of average monthly temperature and precipitation during the period 1950–2000 for the CN-Xi2 site.