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Original Articles

Dynamics of grassland carbon sequestration and its coupling relation with hydrothermal factor of Inner Mongolia

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ABSTRACT

Grassland carbon (C) sink/source evaluation is important to terrestrial ecosystem C cycling research. In this paper, boreal ecosystem productivity simulator (BEPS) model was used to simulate the net ecosystem productivity (NEP) of Inner Mongolia (IM) from 1982 to 2008. The coupling relation between NEP and climate factors was then explored. Results showed that the mean annual value of grassland NEP is 12.2 gC/m^2/yr, and regions with NEP of > 0 (C sink) accounts for 73.2% of the total grassland area of IM. Additionally, the total C sequestration reaches 0.35 Pg C yearly. NEP was positively correlated with precipitation ($R = 0.31$), and the positive correlation percentage accounted for 90% of total grassland area. But NEP was negative correlated with temperature ($R = -0.11$), and the negative correlation percentage was 72% of case. And the partial correlation coefficient between NEP and precipitation and between NEP and temperature was 0.30 and −0.06 respectively. Meanwhile, the monthly NEP of the grassland is obviously lagging behind the precipitation and temperature, and the lag time is both three months. We defined a precipitation differential (PD) parameter to explore the coupling relation between grassland NEP and precipitation. Generally, areas with positive PD are typically a C sinks (72% of the grassland area of IM). However, regions with negative PD are likely a C source (28% of case). The obtained mean PD value of IM is 18 mm, indicating that IM is a C sink.

Further analysis showed that 69% of regions have positive PD and positive NEP, and 20% of regions have negative PD and negative NEP. This result confirmed that precipitation deficit restrains C sequestration. However, the rest of 11% of regions was sensitive area of carbon sink and carbon source transition. Among 8% of the regions (with negative PD but positive NEP) have insufficient precipitation, although other conditions (i.e., ecological restoration program) are favorable to C sink. Moreover, 3% of the regions (with positive PD but negative NEP) have sufficient precipitation, but have negative NEP because of inappropriate management or low temperature. Thus, appropriate measures that can convert a C source to a C sink are necessary. This paper can serve as a reference for policy makers for the efficient targeted implementation of ecological engineering.

1. Introduction

Grasslands, as one of the most widespread vegetation types, cover approximately 40% of the land surface (Frank et al., 2010) and contain around 30% of global total soil carbon (C) stocks (Anderson, 1991). Therefore, grasslands play an important role in the global C budget (Hunt et al., 2004). C balance is often assessed with net ecosystem productivity (NEP), which is defined as the CO_2 uptake by photosynthesis minus the CO_2 lost by ecosystem respiration (ER) and thus represents the net C accumulation over a given time interval (Randerson et al., 2002). Positive NEP values represent a net C uptake by the ecosystem from the atmosphere, and negative values occur when ecosystems release C to the atmosphere (Zhang et al., 2010). Thus, improved understanding of mechanisms that underlie C dynamics in grassland ecosystems and increase C sink functions are necessary for accurately quantifying global C budgets and mitigating the greenhouse

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effects. Grassland ecosystems are sensitive to climate change that results in great fluctuations of C budget (Kim and Verma, 1990; Watson and Verardo, 2000; Wever et al., 2002; Baldocchi et al., 2004). Grasslands can be a C sink with site-appropriate management (i.e., stocking rates) (Owensby et al., 2006; Zhu, 2011) and adequate precipitation. Furthermore, grassland NEP significantly increases with precipitation increase (Rigge et al., 2013). However, precipitation deficits and interannual variability often limit NEP; this result causes grasslands to become a net C source during drought years (Meyers, 2001; Zhang et al., 2010).

Grasslands account 40% of the national land area in China. Moreover, temperate grassland is the main type. Meanwhile, typical grassland areas in Inner Mongolia (IM) are important and representative of parts of the Eurasian temperate grassland ecosystem (Bai et al., 2008). Located in the typical research field zone of global change research of International Geosphere-Biosphere Program IGBP, IM is one of the regions most sensitive to climate change (Steffen et al., 1992). Thus, IM is the typical region for studying C sink/source and response of C dynamics to climate change.

Significant climate changes in temperate grasslands in China over the past 50 years (Qin, 2002; Shi, 2003) have certainly affected the plant productivity and the C budget of this region (Xiao et al., 1995). Furthermore, the spatial patterns of gross ecosystem productivity are determined by mean annual precipitation (MAP) and mean annual temperature (MAT), whereas NEP is largely explained by MAT (Yu et al., 2013). The temperate grassland NEP of northern China has significant correlation with precipitation during 2001–2010, and C uptake in this region is sensitive to precipitation and drought (Zhang et al., 2014). Other studies found that positive correlations exist among grassland net primary productivity (NPP), NEP, and precipitation (Dai et al., 2016). Furthermore, close relationships exist between grassland productivity and precipitation temporal–spatial dynamics, especially in arid and semiarid grassland (Bai et al., 2004).

However, these studies disregarded the complex connection between NEP and climate factors, including the quantity of precipitation needed to induce a C sink. In this study, we selected IM as the study area to simulate the typical temperate grassland NEP based on remote sensing data and climate data using the boreal ecosystem productivity simulator (BEPS) model. Considering spatial patterns, we then quantitatively analyzed the relationship between NEP and climate factors from 1982 to 2008.

The main objectives of this study are following: (1) to analyze the spatial–temporal dynamics of the grassland NEP in IM, (2) to explore the coupling relation between NEP and precipitation and between NEP and temperature at pixel scales, and (3) to determine the quantity of precipitation needed to induce a C sink. Comprehensively describing the connections between NEP and precipitation and between NEP and temperature may provide insights for improving the suitability of grassland resource and enhancing C sequestration in IM.

2. Materials and methods

2.1. Study area

The Inner Mongolia Autonomous Region, which is located between 37.82°–53.82° N and 97.81°–126.80° E with a mean elevation of 1014 m, is ranked as the third largest region in China (Fig. 1). IM is characterized by an arid to semiarid continental climate with strong climatic gradients and varied land-use practices. The region can be divided into three biomes: the arid desert in the west, grassland in the center, and forest in the north-eastern region. Grassland is the dominant vegetation type in IM comprising more than 20% of China's total grassland. A strong east-to-west precipitation gradient results in a decrease in annual precipitation from more than 500 mm in eastern IM to less than 100 mm in the western part.

Owing to the large range of precipitation, three major zonal grassland types—meadow steppe, typical steppe, and desert steppe—are distributed along the north-east to south-west axis in IM. Typical steppe, which developed under semiarid conditions with annual precipitation from 200 mm to 400 mm and annual mean temperature from 0 °C to 8.8 °C in central IM, is the most widely distributed type (Piao et al., 2006). Meadow steppe, which is more productive than a typical steppe, developed in areas with moist fertile soils rich in organic matter in northeastern IM, with annual average precipitation ranging from 300 mm to 600 mm and annual mean temperature from 2 °C to 5.8 °C. The desert steppe, which is found in areas with annual precipitation between 150 mm and 200 mm and annual mean temperature between 5 °C and 10.8 °C, has the least biomass (John et al., 2009).

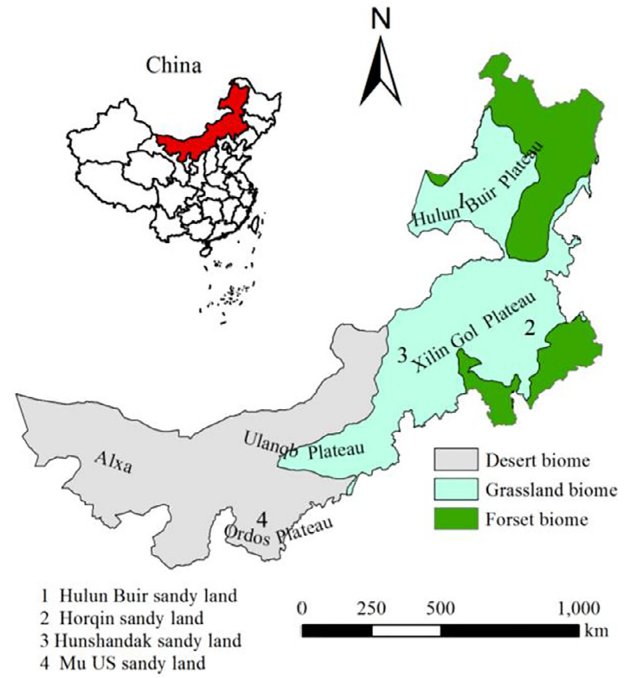

Fig. 1. Location map of the study area Inner Mongolia of People's Republic of China.

2.2. Model description

The BEPS model is a process-based, remote sensing-driven ecological model and originally designed to simulate NPP of terrestrial ecosystems at regional or global scales (Liu et al., 1999). BEPS (boreal ecosystem productivity simulator) model was recently updated to include a module for photosynthesis calculation (Chen et al., 1999), and a CENTURY model-driven soil scheme was incorporated into the model to account for heterotrophic respiration (Rh) and NEP (Potter et al., 1993; Ju and Chen, 2005; Ju et al., 2006). Although the BEPS model was originally applied to boreal forest ecosystems, the optimization of parameters made it now be applied to forest, grassland, and farmland etc. ecosystems. In this model, the solar radiation and photosynthesis were calculated by the separation of the sunshine leaf and shade leaf, and the effect of the leaf shape and structure of different vegetation was reduced by the leaf aggregation index. Meanwhile, other biophysical parameters of different vegetation have also been optimized. Recently, it has been used to estimate NPP and NEP across China's landmass through model advancing (Feng et al., 2007; Wang et al., 2011a,b; Chen et al., 2017). In this study, BEPS was executed at daily time steps for each pixel, and the annual NEP was obtained as the sum of daily NEP values for IM grassland ecosystem. In this paper, we described only the major methods used in calculating indexes of terrestrial C flux (i.e., NPP, Rh, and NEP) and some parameter modifications. The detailed introduction of the model can be found in Ju et al. (2006). NEP is the