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Net ecosystem productivity of temperate grasslands in northern China: An upscaling study

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A B S T R A C T

Grassland is one of the widespread biome types globally, and plays an important role in the terrestrial carbon cycle. We examined net ecosystem production (NEP) for the temperate grasslands in northern China from 2000 to 2010. We combined flux observations, satellite data, and climate data to develop a piecewise regression model for NEP, and then used the model to map NEP for grasslands in northern China. Over the growing season, the northern China's grassland had a net carbon uptake of 158 ± 25 g C m^{-2} during 2000–2010 with the mean regional NEP estimate of 126 Tg C. Our results showed generally higher grassland NEP at high latitudes (northeast) than at low latitudes (central and west) because of different grassland types and environmental conditions. In the northeast, which is dominated by meadow steppes, the growing season NEP generally reached 200–300 g C m^{-2}. In the southwest corner of the region, which is partially occupied by alpine meadow systems, the growing season NEP also reached 200–300 g C m^{-2}. In the central part, which is dominated by typical steppe systems, the growing season NEP generally varied in the range of 100–200 g C m^{-2}. The NEP of the northern China's grasslands was highly variable through years, ranging from 129 (2001) to 217 g C m^{-2} growing season^{-1} (2010). The large interannual variations of NEP could be attributed to the sensitivity of temperate grasslands to climate changes and extreme climatic events. The droughts in 2000, 2001, and 2006 reduced the carbon uptake over the growing season by 11%, 29%, and 16% relative to the long-term (2000–2010) mean. Over the study period (2000–2010), precipitation was significantly correlated with NEP for the growing season ($R^2 = 0.35$, p-value < 0.1), indicating that water availability is an important stressor for the productivity of the temperate grasslands in semi-arid and arid regions in northern China. We conclude that northern temperate grasslands have the potential to sequester carbon, but the capacity of carbon sequestration depends on grassland types and environmental conditions. Extreme climate events like drought can significantly reduce the net carbon uptake of grasslands.

1. Introduction

Grasslands are one of the most widespread vegetation types comprising about 40% of the Earth's terrestrial land area, excluding areas of permanent ice cover (World Resources Institute, 2000). Grassland ecosystems play an important role in the global carbon

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cycle (Adams et al., 1990; Parton et al., 1995) and in livestock development (Reynolds et al., 2005). It was reported that grasslands (including tundra) store one fifth of the global total carbon (485 Pg C) in both vegetation and soil (Adams et al., 1990). Many studies have suggested that grassland ecosystems function as potential carbon sinks or are near equilibrium with respect to carbon exchange (Scurlock and Hall, 1998; Frank and Dugas, 2001; Sims and Bradford, 2001; Suyker et al., 2003; Janssens et al., 2003; Xu and Baldocchi, 2004; Gilmanov et al., 2006; Svejcar et al., 2008). For example, a southern Great Plains mixed-grass prairie has been identified as a carbon sink (Sims and Bradford, 2001); however, a native tallgrass prairie in Texas (Dugas et al., 1999), non-grazed mixed-grass prairie in North Dakota (Frank and Dugas, 2001), and tallgrass in Oklahoma (Suyker et al., 2003) were found to be near equilibrium in terms of carbon. Although these studies suggested that grasslands might be carbon sinks or near equilibrium, alternation between acting as a carbon sink or source frequently occurs (Novick et al., 2004; Gilmanov et al., 2007). For example, a switch from sink to source was observed in a pasture in the southern Great Plains (Meyers, 2001), in a Canadian temperate mixed prairie during drought (Flanagan et al., 2002), and in a warm temperate grassland in southeastern U.S. after harvesting (Novick et al., 2004).

Soil water stress was found to be the main factor regulating the annual net ecosystem production (NEP) in the northern temperate grasslands (Flanagan et al., 2002; Suyker et al., 2003; Hunt et al., 2004; Fu et al., 2006). Therefore, extreme events, such as droughts, can significantly influence interannual variation in terrestrial carbon sequestration in grassland ecosystems, and even switch ecosystems from a carbon sink in a normal year to a carbon source in a drought year (Kim et al., 1992; Meyers, 2001; Gilmanov et al., 2007; Granier et al., 2007; Nagy et al., 2007; Pereira et al., 2007; Aires et al., 2008; Arnone et al., 2008; Kwon et al., 2008; Zhang et al., 2011). Identifying the effects of climate change and extreme events on grassland carbon dynamics is critical for predicting the response of grassland production to future climate change (Parton et al., 1995). However, large uncertainties exist with respect to the role of grasslands in the global carbon budget and their response to climate change under various climatic scenarios and management regimes (Jones and Donnelly, 2004; Verburg et al., 2004; Piao et al., 2007). For example, Scurlock and Hall (1998) suggested that carbon storage in tropical grasslands and savannas may have been underestimated, and Fu et al. (2006) and Ma et al. (2010) showed that different grassland ecosystems might respond differently to climate change in the future.

China's grasslands make up ~10% of total world grassland area and they have been estimated to store 9–16% (Ni, 2002) or 4.4–11.9% (Fan et al., 2008) of the total world grassland carbon. The extensive grasslands in China provide an opportunity to enhance terrestrial carbon sinks, which could have significant effects on carbon cycles both globally and in arid lands (Ni, 2002). Grasslands are the dominant ecosystem type in China and account for 40% of the national land area (Kang et al., 2007; Xu et al., 2008). The grasslands in northern China account for about 78% of the grasslands in China (Sun, 2005), and are an important component of the Eurasian temperate steppes (Bai et al., 2008). The temperate grasslands of northern China are located in the arid and semi-arid climate zones (Bai et al., 2008) and are strongly influenced by the East Asian monsoon. Grasslands in arid and semi-arid regions are ecologically fragile and sensitive to climate change and human disturbances (Gao and Reynolds, 2003; Li et al., 2005), especially to changes in precipitation (Sala et al., 1988; Knapp and Smith, 2001; Ma et al., 2007; Guo et al., 2012).

It is predicted that heat waves and droughts will become more frequent in the 21st century (IPCC, 2007). Moreover, climate change is predicted to cause variations and trends in extreme weather events such as extreme precipitation that will not only affect annual precipitation but will also be manifested in seasonal variations (Easterling et al., 2000). Precipitation and droughts are usually limiting factors in controlling primary production in the arid and semi-arid grassland ecosystems (Kang et al., 2007). The northern China steppe frequently suffers from drought and water stress (Fu et al., 2006). The precipitation in arid and semi-arid regions is highly variable both temporally and spatially. Fluctuations in vegetation production have been found to be closely associated with interannual and intra-annual variations in precipitation in arid and semi-arid ecosystems (Bai et al., 2004; Niu et al., 2008; Shen et al., 2008; Du et al., 2012), and widespread and persistent droughts have caused a general decrease in vegetation productivity in the grassland systems of northern China (Xiao et al., 2009).

Previous studies have presented carbon storage estimates for grasslands of China at a national level using global databases and statistical data, field surveys or investigations, and satellite-based statistical models (Ni, 2001, 2002, 2004; Piao et al., 2007; Fan et al., 2008). However, our knowledge of carbon dynamics and their feedbacks to climate change in the grasslands of northern China remains limited, owing, in part, to a lack of in situ measurements and the spatial heterogeneity in grassland biomass (Ma et al., 2010). Therefore, studies of the impact of climatic conditions on productivity in this area are of significance to understanding both the carbon cycling processes of the grassland ecosystems and the role of grasslands in the national and global carbon budgets.

The NEP is a useful indicator for ecosystem carbon budgets; it represents the net exchange of carbon between terrestrial ecosystems and the atmosphere and is determined by both photosynthetic processes and autotrophic and heterotrophic respiration. The growing network of eddy covariance flux towers provides a synoptic record of the exchange of carbon, water, and energy between the ecosystem and the atmosphere (Baldocchi et al., 2001). These tower sites provide valuable measurements for ecosystem carbon and water exchange worldwide (Yu et al., 2006; Law, 2007). Recently, data-driven upscaling models that integrate flux tower data and remotely sensed environmental variables have been developed for estimating and quantifying terrestrial CO_2 exchange on multiple spatiotemporal scales (Turner et al., 2003; Yang et al., 2007; Wylie et al., 2007; Xiao et al., 2008; Sims et al., 2008; Jung et al., 2009; Zhang et al., 2007, 2010, 2011). Their results showed that the upscaling method is effective for providing highly accurate spatial estimates of vegetation productivity. However, there have been relatively few studies focusing on temperate grassland ecosystems in the northern hemisphere at the regional scale (Wylie et al., 2006; Zhang et al., 2011).

In this study, we used a piecewise regression tree approach (PWR) driven by the long-term satellite and meteorology datasets to upscale eddy flux NEP to the entire grasslands of northern China. The objectives of our study were to: (1) develop a rule-based piecewise regression model to map NEP with Moderate Resolution Imaging Spectroradiometer (MODIS) data and flux tower measurements; (2) map NEP for grasslands in northern China for the period 2000–2010; and (3) quantify the interannual variability of NEP from 2000 to 2010. Our study will provide a better understanding of the magnitude of carbon fluxes and the mutual feedback of terrestrial ecosystems over northern temperate grasslands.

2. Materials and methods

2.1. Study area and flux tower data

This study was conducted in the temperate grasslands of northern China across three provinces: Inner Mongolia, Gansu, and Ningxia (Fig. 1). The study region is characterized by arid and semi-arid conditions and is strongly influenced by the East Asian