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Estimating net primary production of natural grassland and its spatio-temporal distribution in China

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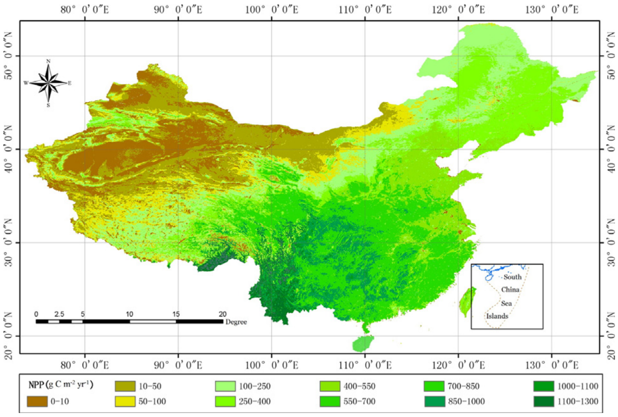
HIGHLIGHTS

- To simplify the input parameters, the CASA was improved based on CSCS.
- $\Sigma\theta$ and K were used and referred to estimate moisture stress coefficients in CASA.
- High level of coupling between grassland NPP and classes and super-classes in CSCS
- A suitable combination of water and thermal is a key driver of dynamical changes in NPP.

GRAPHICAL ABSTRACT



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ABSTRACT

The net primary production (NPP) of grassland largely determines terrestrial carbon (C) sinks, and thus plays an important role in the global C cycle. Comprehensive and sequential classification system of grasslands (CSCS) is a unique vegetation classification system (mainly for grassland) that is dependent on quantitative measurement indices [>0 °C annual cumulative temperature ($\Sigma\theta$) and moisture index (K-value)]. Based on the relationship of the quantitative classification of CSCS and grassland NPP, a modified model of Carnegie–Ames–Stanford Approach (CASA) was used to predict the grassland NPP and its temporal and spatial distribution in China from 2004 to 2008. The scatter plot of the estimated NPP and the observed NPP showed that the estimated data can be accepted with correlation coefficient of 0.896 ($P < 0.05$). The average annual NPP of grassland from 2004 to 2008 in China ranged from 443.23 to 554.40 g C m^{-2} $yr.^{-1}$. The NPP also showed spatial–temporal variations. There existed an increasing trend of NPP from the northwest to southeast due to the zonal distribution of vegetation. From the trend of monthly variations, it can be drawn that the NPP accumulation primarily occurred between April and October. The average NPP over seven months from April to October was 482.19 g C m^{-2}, or about 88.78% of the annual total. The spatial–temporal trend suggests the importance of water and thermal regimes in determining the grassland NPP (i.e. water and thermal are key limited factors for the grassland production), which is also confirmed by a cluster analysis. The mean annual NPP and the total annual NPP differed significantly

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among grassland classes corresponding with different Σθ and K-value. The results demonstrate that the grassland NPP and the classes/super-classes in CSCS achieve the optimum coupling.

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1. Introduction

Terrestrial net primary production (NPP), an indicator of the accumulation of atmospheric CO_2 in terrestrial ecosystems, plays crucial roles in global change (Keeling et al., 1996; Roxburgh et al., 2005). NPP is a major determinant of carbon (C) sinks on land and a key moderator of ecological processes (Potter et al., 1993). In recent decades there has been a significant focus, quite rightly, on terrestrial NPP at global and regional scales and on factors affecting it (Cramer et al., 1999; Lehuger et al., 2010). Previous works have been conducted to estimate NPP to determine the evolution of terrestrial ecosystems and study its response to global change (Field et al., 1995; Piao et al., 2006; Eisfelder et al., 2014). Grasslands play an important role in the global C cycle (Hall et al., 1995). The magnitude of grassland NPP is determined interactively by soil, grass types, and livestock in grassland ecosystem and climate factors such as temperature, precipitation, and relative humidity (Lauenroth et al., 2006; Lin et al., 2013). NPP directly reflects the production capacity of grassland communities. Thus, it is important to understand the current and potential role of grassland C emissions and sequestration (Maselli et al., 2013; Wang et al., 2014).

It is rather difficult to estimate terrestrial NPP on a large scale by the direct harvest method. Thus, it is necessary to use mathematical models, calibrated with existing data, to investigate the spatial and temporal variations of NPP (Lin, 2009). There are several models for estimating NPP, including climate-based models (Lieth, 1972), light-use efficiency model (Potter et al., 1993), and mechanistic ecological process models (Parton et al., 1993). For example, the Miami model was the first NPP model which uses an empirical regression to relate NPP to the annual average temperature and precipitation without accounting for other factors (Lieth, 1972). The Thornthwaite Memorial model was established based on the data used in the Miami model, but was modified to include Thornthwaite's potential evaporation model (Lieth, 1977). With the development of remote sensing techniques, a large number of models based on satellite data are commonly used in simulating NPP of terrestrial ecosystems (Potter et al., 1993; Field et al., 1995; Potter, 2014; Liang et al., 2015). Carnegie–Ames–Stanford Approach (CASA) is a light-use efficiency model which relates NPP directly to vegetation characteristics and environmental variables or indicators such as temperature, precipitation, and solar radiation (Potter et al., 1993; Field et al., 1995). The CASA model has been successfully implemented by several researchers to simulate NPP over North America, South America, Eurasia, Australia, and Africa at a range of spatial and temporal scales (Field et al., 1995; Hicke et al., 2002; Piao et al., 2006; Tang et al., 2014). Based on the CASA models, many studies have been conducted to estimate the distribution of terrestrial NPP in China and its responses to global climate change (Piao et al., 2005, 2006; Gao and Liu, 2008; Yu et al., 2009; S.N. Liu et al., 2012). However, there are some important limitations in the CASA. Firstly, the maximum light use efficiency (ε_{max}) was set to 0.389 g C MJ^{-1} for all vegetation types in the CASA model (Potter et al., 1993; Field et al., 1995). However, owing to the differences such as vegetation type, life type, ε_{max} for different vegetation should not be the same value (Yu et al., 2008). Secondly, moisture stress coefficients in the CASA model were calculated by the soil moisture model which is related to many soil parameters (field moisture capacity, the wilting coefficient, the percentage of soil sand and clay particles, and the depth of the soil (Potter et al., 1993). In general, it is difficult to obtain credible values of these soil parameters. Moreover, they are extracted from a soil class map whose accuracy is low on a large geographical scale (Yu et al., 2009).

China has about 400 million hectares (M ha) of grassland, accounting for about 41.7% of the country's land area (Chen and Fischer, 1998). The grasslands are mainly distributed in the western and northern regions, and the area of natural grasslands of north China (about 313 M ha) covers 78% of total grassland area of the country (Chen and Fischer, 1998). During the past 60 years, strong efforts have been made to improve the production of grassland and livestock systems and maintain the ecological equilibrium in these regions. For example, the theory and method of grassland classification have been widely studied in China. Comprehensive and Sequential Classification System of grasslands (CSCS) is formulated through grouping or clustering units with similar properties (Ren et al., 2008). Up to date, the distribution maps for grassland classes at the global and national scales have been completed by the CSCS (Liang et al., 2012; X. Liu et al., 2012). The use of the CSCS was compatible with geographic information system and spatial analytical methods. It is feasible to predict the distribution of grassland vegetation under given climate conditions by linking these methodologies (Ren et al., 2008). Moreover, use of the CSCS and related theory to study grassland succession associated with global climate change may be a new research approach.

Based on the CSCS, the present study has made improvements in the CASA model in the following two aspects: (1) to exclude several soil parameters, >0 °C annual cumulative temperature (Σθ) and moisture index (K-value) in CSCS were used and referred to the existing regional evapotranspiration model to estimate moisture stress coefficients; (2) the values of ε_{max} were estimated for different grassland classes according to the principle of minimal error between the estimated and the observed NPP. Then, the grassland NPP in China from 2004 to 2008 was estimated by the improved CASA, and it was generally comparable to that of the validation data from field observations and two climate-based NPP models (the Miami model and the Thornthwaite Memorial model). Additional analysis of the changes in grassland NPP from 2004 to 2008 in China was also carried out. Therefore, the main objectives of this study are to (1) improved the CASA based on CSCS in order to simplify the input parameters; and (2) using this modified CASA model to estimate the NPP of China's grassland from 2004 to 2008 and analyze its spatial distribution.

2. Materials and methods

2.1. Study area

The entire land area of China selected for this study is geographically situated between 3°51′ and 53°31′ North latitude and between 73°40′ and 135°2′ East longitude, and the focus was on grasslands. The climate of China is extremely diverse due to its wide coverage, assortment of terrains as well as the different distances to the sea from different locations. It ranges from tropical regions in the south to subarctic in the north. Following the above gradients, the land cover is also changing, ranging from agricultural areas to forests and pastures.

2.2. NDVI data set

MODIS NDVI used in the modeling was acquired from National Aeronautics and Space Administration (NASA, http://ntrs.nasa.gov/search.jsp). The spatial resolution was 1 × 1 km. The temporal resolution is 16 days. Date range for the MODIS data was from January 2004 to December 2008. The data were processed with radiometric calibration using the NOAA standard method (Rao and Chen, 1995) and atmospheric corrections, including ozone absorption using the method of

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