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Analysis of spatial and temporal patterns of net primary production and their climate controls in China from 1982 to 2010

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ABSTRACT

Ecosystem net primary production (NPP) represents vegetation biomass increment after accounting for autotrophic respiration and is recognized as an important component of the terrestrial carbon cycle. In this study, the spatial and temporal patterns of NPP and their climate controls in China's ecosystems for the period of 1982–2010 were analyzed by using a remote sensing-based carbon model (i.e., the Carnegie–Ames–Stanford Approach, CASA) and multiple statistical methods. Validation against NPP observations from 335 forests sites showed good performance of CASA over the study region, with an overall coefficient of determination (R^2) of 0.73 and root mean square error (RMSE) of 132.9 g C m^{-2} yr^{-1}. Spatially, we found that the spatial pattern of China's NPP showed gradients decreasing from the southeast toward northwest, which could be mainly explained by the spatial variability in annual precipitation. Temporally, China's NPP showed a significant increasing trend at both the national and biome levels during 1982–2010, with an annual increase of 0.011 Pg C or 0.42%. However, the increasing trends in NPP were not continuous throughout the 29-year period at the national scale. On the other hand, it showed three periods where the trends changed, which was likely being caused by a shift in climate conditions and extensive drought. Air temperature was found to be the dominant climatic factor that controlled the interannual variability in NPP throughout the country except for arid and semi-arid regions in the middle-north and northwest parts of China, where the interannual variations in NPP were mainly explained by changes in precipitation. Similar results were also obtained at the seasonal scale that changes in NPP were generally controlled by that in air temperature except for summertime, in which higher NPP were favored by higher summer precipitation, whereas summer temperature was negatively correlated with NPP. At the monthly scale, NPP responded to change in temperature more rapidly than that in precipitation. However, temperature appeared to control NPP only in humid and semi-humid regions. For monthly NPP–precipitation relationship, the strongest positive relations were observed when NPP lagged behind precipitation by 1–3 months. However, deviating from the common hypothesis that plant in drier areas should respond to water availability more rapidly than in other regions, our analysis revealed a relative large time lag between monthly NPP and precipitation in arid ecosystems (i.e., 3 months). This result suggests that there may be a more complex mechanism of local water redistribution that controls vegetation water use (e.g., use of water from previous year precipitation) in extremely arid ecosystems.
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1. Introduction

Knowledge of the global carbon budget is essential for developing policies for global climate change (Piao et al., 2008; Schulze et al., 2000; Wofsy and Harriss, 2002). Net Primary Production (NPP) is one of the main components of the carbon cycle and represents the biomass increment of both above- and below-ground

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Table 1
Summary of studies on NPP in China.

Methods	Study periods	NPP ranges (Pg C yr^{-1})	References
Miami model	1992	3.719	Sun and Zhu (2000)
LUE model	1992	2.645	Sun and Zhu (2001)
CASA model	1982–1999	1.5–2.1	Piao et al. (2001)
LUE model	1990	6.13	Chen et al. (2002)
CEVSE model	1981–1998	2.86–3.37	Cao et al. (2003)
CASA model	1982–1999	1.44	Fang et al. (2003)
BEPS model	2001	2.24	Feng et al. (2007)
C-Fix model	2003	4.37	Chen and Wang (2007)
CASA model	1989–1993	3.12	Zhu et al. (2007)
GLOPEM model	1981–2000	2.76–3.31	Gao and Liu (2008)
CEVSA model	1980–2000	3.13–3.68	Gao and Liu (2008)
GEOPRO model	2000	2.42	Gao and Liu (2008)
GEOLUE model	2000–2004	2.84	Gao and Liu (2008)
LPJ model	1981–1998	2.91–3.37	Sun (2009)
M-SDGVM	1981–2000	3.30	Mao et al. (2010)
CASA model	1981–2008	3.38–4.35	Chen et al. (2011)
BEPS model	2000–2010	2.63–2.84	Liu et al. (2013)
CASA model	2001–2010	2.25–2.62	Pei et al. (2013)

vegetation components after accounting for autotrophic respiration. NPP thus contributes to human welfare because it is the basis for food, fiber, and wood production. Therefore, understanding the spatial and temporal patterns of NPP and its interactions with environmental factors (i.e., climate factors and anthropogenic factors) has been the foci of global change studies during the past several decades (e.g., Ei-Masri et al., 2013; Fang et al., 2003; Hemming et al., 2013; Piao et al., 2005; Zhao and Running, 2010).

China, in parallel with its recent economic boom, has become the largest CO_2 emitter since 2006 (~1.5 Pg C yr^{-1}) (Gregg et al., 2008). On the other hand, China has a vast land area, encompasses a wide range of ecosystems and climates, providing a great potential for biological carbon sequestration or harvesting (Piao et al., 2009). China thus plays a key role in determining the carbon budget at regional (i.e, Eurasia) or even global scales (Piao et al., 2009). Further, China has experienced largely-altered hydro-climatic conditions and extensive changes in land use and land cover since the reform and opening policies (government economic policies) in the late 1970s, which leads to large variations in China's terrestrial ecosystem production (Liu et al., 2003; Piao et al., 2010). Therefore, examining spatiotemporal patterns of China's NPP and its environmental controls will advance our understanding of regional/global carbon budgets in a changing environment and consequentially help with forecasts of the potential biosphere feedback to natural and anthropogenic changes in the climate system.

In addition to understanding where and when China's NPP changed, it is more critical to investigating causes of those changes in NPP, as it is the key to predict NPP patterns in the future. Water availability and temperature are two main climatic variables that determine the spatial distribution of ecosystems and the variations in their productivity (Campos et al., 2013; Yang et al., 2013a). China has a wide range of bio-climates, from tropical rainforests in the south to boreal mixed forests in the northeast and temperate deserts in the northwest. China also encompasses the "third pole" of the Earth, i.e., the Qinghai–Tibetan Plateau, which is generally considered as one of the most sensitive zones to climate change in the world (Piao et al., 2006a; Yang et al., 2014a; Yu et al., 2010). The great diversity of bio-climate zones in China provides a good opportunity for identifying effects of climate change on vegetation activity and their variations.

In this paper, we presented an investigation of spatial and temporal patterns of NPP and its climate controls over China from 1982 to 2010 by using a remote sensing-based carbon model, i.e., the Carnegie–Ames–Stanford Approach (CASA) (Potter et al., 1993). The CASA model has been successfully applied to mapping NPP patterns worldwide, including in mainland China (e.g., Fang et al., 2003; Pei et al., 2013; Piao et al., 2005). Compared with process-oriented ecosystem models that entail a complex combination of model parameterizations, the remote sensing-based approaches are relatively simpler and more efficient for exploring dynamic changes in NPP and their spatiotemporal variations at larger scales. Moreover, satellite remote sensing provides information about the integrated response of vegetation canopies to environmental factors, including those that might otherwise be neglected in model mechanisms, such as land use change, irrigation, as well as nature hazard (Malmstrom et al., 1997; Hicke et al., 2002). Although previous studies have reported some results on NPP in China, most of them were limited at specific regions or within shorter periods. For example, Piao et al. (2005) investigated variations in NPP of China from 1982 to 1999, whereas Liu et al. (2013) focused on a period of 2000 through 2010 (see Table 1 for summary). It is further noticed that China's NPP estimates from different studies differ remarkably, spanning a range from 1.5 Pg C yr^{-1} in Piao et al. (2001) to 6.13 Pg C yr^{-1} in Chen et al. (2002). Inconsistencies among studies have imposed a big question mark regarding the findings and greatly hindered a better understanding of the variations in NPP of China in the long run. In addition, recent studies have suggested that the warming trend and greening trend may have slowed down during the first decade of the 21st century in comparison to those in 1980s and 1990s (Buermann et al., 2007; Cane, 2010). To that end, a consecutive study on NPP covering the whole period of the past three decades is imperative, which would potentially provide a greater insight into the trajectories for both climate and vegetation. We hypothesize that the diminished warming and greening trends would have led to a shifting pattern in China's NPP trends in more recent decades. As a result, the main objectives of this study were to: (1) examine the spatial pattern of NPP in China and its controlling climate factors; (2) understand interannual variability of NPP in China for the period 1982– 2010; and (3) investigate the NPP–climate relationships at different timescales, i.e., annual, seasonal, and monthly.

2. Data and method

2.1. CASA model

The CASA model is a light use efficiency-based NPP model, in which the NPP is estimated as the product of the amount of photosynthetic active radiation absorbed by green vegetation (APAR, MJ m^{-2}) and the light use efficiency (ϵ, g C MJ^{-1}) that converts the APAR into plant biomass increment (Potter et al., 1993; Field et al.,

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