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The temporal and spatial patterns of terrestrial net primary productivity in China

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In this paper, we use CEVSA, a process-based model, which has been validated on regional and global scales, to explore the temporal and spatial patterns of Net Primary Productivity (NPP) and its responses to interannual climate fluctuations in China´s terrestrial ecosystems over the period 1981-1998. The estimated results suggest that, in this study period, the averaged annual total NPP is about 3.09 Gt C/yr-1 and average NPP is about 342 g C/m2. The results also showed that the precipitation was the key factor determining the spatial distribution and temporal trends of NPP. Temporally, the total NPP exhibited a slowly increasing trend. In some ENSO years (e.g. 1982, 1986, 1997) NPP decreased clearly compared to the previous year, but the relationship between ENSO and NPP is complex due to the integrated effects of monsoons and regional differentiation. Spatially, the relatively high NPP occurred at the middle high latitudes, the low latitudes and the lower appeared at the middle latitudes. On national scale, precipitation is the key control factor on NPP variations and there exists a weak correlation between NPP and temperature, but regional responses are greatly different.

The temporal and spatial patterns of terrestrial net primary productivity in China TAO Bo1, LI Kerang1, SHAO Xuemei 1, CAO Mingkui2 (1. Inst. of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China; 2. Department of Geography, University of Maryland, USA) 1 Introduction Net primary productivity (NPP), the key component of biogeochemical cycle in the terrestrial biosphere, is defined as the amount of dry matter produced by plants per unit of time and space. NPP reflects the capacity of plants to capture and use solar radiation and its dynamics variations control the spatio-temporal patterns of carbon sink and sources in terrestrial ecosystems. The spatio-temporal characteristics of NPP depend on the complex interactions among vegetation, soil, and climate and were intensively influenced by human activities and global environmental change (Schimel et al., 1995). Presently, the estimation of NPP dynamics on large scales (regional, national, and global) still remains large uncertainties and the underlying reasons has not been clearly elucidated. So the accurate estimation of NPP and exploration of its interrelationship with controlling factors are of great significance to enhance the understanding of spatio-temporal patterns of carbon sink and sources, reduce the uncertainties in the study of carbon cycle, and predict the future trajectory of climate change. The patterns of NPP vary spatially with the regional environmental conditions, climatic factors, and vegetation types on spatial scales and spans from seasons, interannual to decadal levels on temporal scales. Traditionally, sample surveys and field measurements are applied to estimate NPP, but these methods are hard to extend to the estimations of NPP on large scales because of the sparse measurements network and the substantial expenditure. With the increasing accumulation of field data and improved understanding of ecosystems, modeling method has been a powerful tool in accurate estimation of NPP on large scales. Process-based ecosystem models describe mechanistic processes of ecosystem carbon cycle and their dynamic responses to changes in environmental conditions. Model simulation has been widely used in quantification of spatio-temporal variations in ecosystem carbon fluxes and analyses of the underlying mechanisms on regional and global scales (Cao and Woodward, 1998a; Cao and Woodward, 1998b; Liu et al., 1999; Li and Ji, 2001). Modern ecosystem models are developed based on extensively tested algorithms, and have been used extensively in global change studies. As these models are driven with actual changes in environmental conditions and ecosystem pattern (such as vegetation distribution and composition), they could realistically capture the spatio-temporal patterns in terrestrial carbon fluxes and have been an essential tool to explore ecosystems to climate change and the interacti ons between vegetation and environmental factors. In the last decade, many studies have been conducted to estimate the spatial patterns of China´s terrestrial NPP and carbon storage in vegetation and soils (Zhu, 1993; Zhang, 1993; Zhou and Zhang, 1996; Sun and Zhu, 2001; Cheng, 2001; Liu, 2001). Moreover, few studies focus on the interannual variations of NPP and its responses to climate change. In this study, we use a biogeochemical model, CEVSA (Cao and Woodward, 1998a; 1998b), to quantify the dynamic responses of China´s terrestrial NPP to climate change at 0.5o and a time step of month. The aim is to enhance the understanding of the spatio-temporal patterns of China´s terrestrial NPP, its controlling factors, and the mechanisms of the responses to climate change. 2 Data and methodology 2.1 Model CEVSA is a biogeochemical model to estimate carbon fluxes between vegetation, soils, and atmosphere, based on the process of photosynthesis, autotrophic respiration, litter production, and heterotrophic respiration (HR), which are controlled by the eco-physiological characteristics of biomes (e.g. photosynthetic pathway, leaf form, and phenology) and by environmental conditions (e.g. radiation, temperature, water, and nutrient). To couple these biological and environmental controls over ecosystem carbon fluxes, CEVSA (Cao and Woodward, 1998a; 1998b) includes three modules (Figure 1): the biophysical module calculates the transfer of radiation, water, and heat to determine canopy conductance, evapotranspiration and soil moisture; the plant growth module describes photosynthesis, autotrophic respiration, carbon allocation among plant organs, leaf area index (LAI) and litter production; the biogeochemical module simulates the transformation and decomposition of organic materials and nitrogen inputs and outputs in soils. The detailed descriptions of the model are given in Cao and Woodward (1998b) and Woodward et al. (1995). The key processes in the model are as follows. 2.2 Plant photosynthesis and NPP Plant photosynthesis depends on the CO2 utilization efficiency of photosynthetic biochemical processes and CO2 supply by diffusion through stomata into leaf intercellular spaces. The rate of plant CO2 assimilation implied by biochemical processes (Ab) is after Collz et al. (1991): Ab = min {Wc, Wj, Wp} (1 - 0.5Po / ?子 Pc) - Rd (1) where Wc represents the efficiency of photosynthetic enzyme system, specifically the carboxylating enzyme Rubisco, and is related with foliar nitrogen content; Wj is the limitation of electron transport to photosynthesis as a function of incident photosynthetically active radiation (PAR); Wp is the limitation of triose phosphate utilization to photosynthesis, representing the capacity of the leaf to utilize or export the product of photosynthesis; Po and Pc are the internal partial pressure of O2 and CO2 respectively; ?子 is the specificity factor of Rubisco for CO2 relative to O2; and Rd is the rate of respiration in light due to processes other than photorespiration (Harley et al., 1992). Stomatal conductance controls the diffusion of CO2 from the atmosphere into the intercellular air spaces and thus CO2 supply for photosynthesis. The rate of plant CO2 assimilation implied by the stomatal conductance to CO2 (Ad) is after Harley et al. (1992): Ad = gs (Pa - Pc) / 160 (2) gs = (go (T)+g1 (T) A Rh / Pa) kg (ws) (3) where Pa is the partial pressure of atmospheric CO2, and gs is stomatal conductance to water vapor, and go is the stomatal conductance when plant CO2 assimilation is zero at the light compensation point, and g1 is an empirical sensitivity coefficient. A is the actual rate of plant CO2 assimilation. Rh is relative humidity of the air surrounding the leaf. T is absolute temperature. The function kg (ws) describes the response of stomatal conductance to soil water content ws. The above equations show that, plant CO2 assimilation and stomatal conductance interact with each other for keeping a balance between CO2 utilization and supply in the intercellular air spaces, in addition to being affected by many environmental factors. They can only be determined by iteratively solving the nonlinear equations that arises by setting Ad equal to Ab. On canopy scales, the plant CO2 assimilation tightly correlated with LAI and LAI-determined PAR and vertical distribution of nitrogen in leaf. In CEVSA, the plant canopy is divided into layers, each of which has a unit of LAI and the rates of CO2 assimilation and stomatal conductance of each layer are calculated separately. LAI is determined based on the conditions that the net CO2 assimilation in the lowest layer is above zero and the water balance between water supply (from precipitation and soil water storage) and losses through evapotranspiration (Woodward et al., 1995). 2.3 Carbon allocation, accumulation and turnover in vegetation To balance leaf carbon assimilation and root nutrients and water uptake, plants allocate fixed carbon proportionally among leaves, stems (including branches) and roots. For grasses, carbon allocation between leaves, stems, and roots is estimated with fractional parameters (Cao and Woodward, 1998b). For trees and shrubs, the carbon fixed by the plant canopy (AI) is allocated to leaves (CL), stems (CS), and roots (CR) as: AI = CL + CS + CR (4) is calculated as follows: CL = LAIS (5) where S is specific leaf area. According to Givnish (1986), a fraction, f, of AI is allocated to leaves (f) and a fraction, 1-f, to roots, the fraction f is estimated as: f = Rm / (RS + Rm) (6) where Rm is the leaf mesophyll resistance to CO2 uptake, and Rs is the stomatal resistance to water loss (Woodward et al., 1995). Based on the calculated f and CL, CR is given as: (7) Cs is then calculated by difference in equation (4). The carbon allocated to plant organs will either be accumulated, lost through autotrophic respiration, or shed as litter entering into soils. In CEVSA, NPP is calculated as: (8) (9) where Ri and LTi are, respectively, the autotrophic respiration and litter production of lea ves, stems, and roots.

2.4 Model validations

CEVSA model has been used on global and regional scales in quantifying the dynamic responses of terrestrial ecosystem carbon fluxes to climate change (Cao and Woodward, 1998a; Cao et al., 2001; Cao et al., 2002). The ecological theories, equations, and parameters used in CEVSA were developed based on intensively tested algorithms to describe eco-physiological processes involved in ecosystem carbon cycle. Meanwhile, the model estimates of NPP, LAI, and carbon storage in vegetation and soil agree well with field measurements and the data derived from satellite remote sensing (Cao and Woodward, 1998b; Woodward et al., 1995). Figure 2 shows a good correlation between the NPP estimated with CEVSA and from field measurements (Cramer et al., 2001).

2.5 Model running and data sources

We run CEVSA with observation-based data sets of climate, atmospheric CO2, and vegetation distribution to calculate the changes in NPP, HR, NEP, and the carbon stocks in vegetation and soils for the period 1981-1998. The climate data (monthly mean temperature, precipitation, relative moisture, and cloudiness etc.) were supplied by the Climatic Research Unit (CRU), University of Norwich, UK (New et al.,2000). Monthly atmospheric CO2 concentration was derived from the measurements in the Mauna Loa Observatory, Hawaii (Keeling and Whorf, 1999). The information on soil properties was derived from the FAO-IIASA-ISRIC global soil data set (Batjes et al., 1997). The vegetation data set used in this study included 13 land cover types classified using the NOAA/NASA Advanced Very High Resolution Radiometer (AVHRR) data at 8 km resolution (Figure 3) (Defries et al., 1998). Using the climate, vegetation and soil data, we first ran CEVSA with an averaged climate from 1951 to 1998 until an equilibrium was reached, i.e., as the differences between annual NPP, litter production and decomposition, and the interannual variations in soil moisture, carbon storage in vegetation and soils, are less than 0.1%. Then we made dynamic simulations from January, 1951 to December, 1998 with transient changes in climate and atmospheric CO2. In this study, we just analyse the modeled estimates from 1981 to 1998. The run from 1951 to 1980 is for remove the artifacts from the assumption that ecosystems are equilibrium in the initialization run.

3 Results

3.1 Spatial patterns of NPP

The modeled results show that the estimated total NPP fluctuated between 2.89 and 3.37 Gt C yr-1 with a mean value of 3.09 Gt C yr-1. The interannual standard deviation was 0.24 Gt C and fluctuating magnitude (the difference between the maximum and minimum annual NPP) was up to 0.48 Gt C, which was 15.6% of the average value for the period of 1981-1998. The range of the averaged NPP for vegetation types was from 90 g C m-2 yr-1 for open shrubs to 873 g C m-2 yr-1 for evergreen broad-leaved forest. Nationally, NPP averaged about 342 g C m-2 yr-1 in the study period. East monsoon region, including Northeast, North, and Central China accounted for more than 80% of the total NPP on the national scale, whereas Northwest arid regions and Tibet just contributed no more than 20%. The spatial variations in NPP from CEVSA during 1981-1998 in China were plotted (Figure 4). When investigated meridionally, the averaged NPP decreased from southeastern coastal areas of China with appropriate precipitation and temperature for plant growth, to Northwest China with arid climate and sparse vegetation cover. Latitudinally, the distribution patterns of the averaged NPP exhibited two peak areas, i.e., 22oN and 50oN, which were exactly pursuant to Southwest and Northeast forest regions. The higher values of the total NPP mainly occurred in the subtropical regions (25-35oN) and the temperate or middle temperate regions (Figure 5).

3.2 Temporal variations of NPP

Our results showed that the total NPP varied from 2.89 to 3.37 Gt C yr-1, behaving obvious interannual variations. Compared with 1998, 1996, 1994, 1990 and 1985, the total NPP in 1997, 1989, 1986, and 1982 was lower. The maximum and minimum were 3.37 Gt C yr-1 in 1998 and 2.89 Gt C yr-1 in 1989 and 1997, respectively. In the study period, the total NPP in China´s terrestrial ecosystems had a slow increasing trend by 0.32% yr-1 (Figure 6). We also computed the mean total NPP of every six-year period (1981-1986, 1987-1992 and 1993-1998) and 3.04 Gt C yr-1, 3.06 Gt C yr-1, and 3.16 Gt C yr-1 were found, which further confirmed the increasing trend in the whole study period, especially in the latter 1990s. When investigated in natural regions, our results revealed that the magnitude of the total NPP´s increasing varied in different natural regions. Relatively great NPP increases occurred in Northeast China, Central China, and South China. Northwest China had a smaller increase and North China and the middle and lower reaches of the Yangtze River had no significant difference in NPP interannual variations.

3.3 The relationship between interannual variations of NPP and climate change and ENSO

A correlation analysis between estimated NPP and climatic factors (temperature & precipitation) on the national scale showed that precipitation was the most important factor determining the spatial and temporal patterns (R2 = 0.72, p < 0.01). The responses of different natural regions are also analyzed, which revealed that Northeast China (R2 = 0.85, p < 0.01), Northwest China (R2 = 0.97, p < 0.01), Inner Mongolia (R2 = 0.97, p < 0.01), and North China (R2 = 0.96, p < 0.01) had significant correlation with precipitation. In South China, the middle and lower reaches of the Yangtze River, and Central China, where annual precipitation was above 1,200 mm, weak correlation was found due to appropriate precipitation and temperature for plant growth. On national scale, the total NPP had a weak correlation with temperature. Clear correlation was only found in Central China and South China. It was generally believed that NPP would vary with the precipitation and temperature as a result of ENSO

(Michael et al., 2001). It is found that rainfalls and its spatial and temporal variabilities in China during summer and winter are greatly affected by ENSO cycle (Jin et al., 1999). Therefore it is certain that ENSO had impacts on the interannual variations of NPP. Whereas the responses of NPP to ENSO cycle are very complex since much of China has a continental monsoon climate and monsoon circulation changes the patterns of climatic elements greatly. On national scale, NPP had a decrease in some El Nino years, such as 1982, 1986, 1991 and 1997, especially in 1997, the total NPP decreased from 3.31 Gt C yr-1 to 2.89 Gt C yr-1. But also in El Nino years, 1993 and 1994, NPP did not exhibit a significant decrease, even an increase of 0.12 Gt in 1994. The underlying reasons are different regional patterns of temperature and precipitation and different regional responses to El Nino. In 1993, the rainfall was more than normal in most parts of China and summer rainfall was homogeneous in time and space. The summer monsoon over East Asia and Indian Low was weaker than normal. Affected by ENSO event which began in April, the summer rainfall band was southwards and the precipitation in North China and Northwest China were more than normal. But there were no significant differences in mean annual temperature compared to the previous year on national scale. When investigated in regions, the annual precipitation in Northeast China, North China, and Northwest China varied by as much as 5%, 4%, and 9%, respectively. The annual temperature had no significant differences in Northeast China and a little decrease in North China and Northwest China, so the increases of the total NPP occurred in the above regions. In South China, NPP also had an increase in 1993 as a result of the higher temperature and more precipitation compared to the previous year. In the middle and lower reaches of the Yangtze River and Central China, the decrease of temperature led to a decrease in total NPP. In Inner Mongolia, the total NPP had no significant difference as the result of little variations of annual precipitation, though annual temperature had a small decrease. Integrating the variations of NPP in these regions, we found that the increment of NPP in Northeast China, North China, Northwest China, and South China partly counteracted the decrement in the middle and lower reaches of the Yangtze River and Central China, which contributed to just a small decrease in total NPP (1%) compared to 1992. In 1994, annual precipitation in most parts of China increased except the Yangtze-Huaihe river basin, the lower reaches of the Yangtze River, the Hetao Plain, and parts of North China and Northwest China. Affected by monsoon over East Asia and South Asia and ENSO events, summer rainfall band was located in the lower reaches of the Yellow River, the central and northeastern parts of North China. The annual temperature also increased by 0.7oC compared with 1993 on national scale. The total NPP in most parts of China increased except a decrease of 20% in Northwest China and no significant difference in Inner Mongolia compared to 1994. The investigation in regions revealed that increases of 12%, 21%, 2%, 6%, and 3% occurred in Northeast China, the middle and lower reaches of the Yangtze River, North China, Central China, and South China, respectively, which brought an increase of 4% on national scale. 4 Conclusions and discussion 4.1 In the study period, the total NPP in China´s terrestrial ecosystem fluctuated between 2.89 and 3.37 Gt C yr-1 with an average of 3.09 Gt C yr-1. The averaged NPP was 342 C m-2 yr-1. The modeled results showed that NPP had a slight increasing trend, which was mainly related to the increases in atmospheric CO2 concentrations and precipitation in the study period. Our results are comparable to other ecosystem modeling studies, which investigated the interannual variations of NPP on large scales. For example, Goetz et al., using the global production efficiency model (GLO-PEM), indicated that there was a NPP increase in boreal regions for the period 1982-1989 on global scale (2000). Piao et al. indicated that China´s NPP behaved an increasing trend in the period 1982-1999 (2002). The total NPP (3.09 Gt C yr-1) in this study is in the middle of others estimates. For example, it was estimated as 2.65 Gt C yr-1 by Sun et al. using a radiation use efficiency model (Sun and Zhu, 2001), and 3.65 and 4.72 Gt C yr-1 respectively by Xiao et al. using TEM (1998) and Liu using TEPC (Terrestrial Ecosystem Production Process Model in China) (2001). The averaged NPP (342 g C m-2 yr-1) from CEVSA is comparable to 387 g C m-2 yr-1 by Xiao et al. using TEM. In addition, we compared our modeled NPP of various vegetation types with other studies and the available field NPP data, which showed that the results are in the range of field measurements, basically (Table 1). We can also find that a big gap exists among estimates from various studies, which is one of largest uncertainties in NPP modeling. 4.2 In the study period, precipitation was the key factor for interannual variations, but responses of different regions varied greatly. In Northeast, Northwest, and North China, interannual variations of NPP had significant correlations with precipitation. In South China, the Yangtze Valley, and Central China, the correlation between NPP and precipitation was not significant, statistically. On national scale, NPP had a weak correlation with temperature except in South China and Central China. In addition, we found that NPP had clear decreases in some periods of El Nino to La Nina transition. But the relationship between NPP variations and ENSO cycle is complex and more work should be done due to monsoon circulation and the substantial regional responses. Still many problems should be probed, though we get a general view of distribution patterns of NPP and its responses to climate change in China´s terrestrial ecosystems. For examples, relatively low resolution and the short of intercomparsion and validatio

ns due to the availability of field data about the long-term changes in NPP, the impacts of LUCC (Land Use and Land Cover Change) on NPP variations were not considered, and so on. Furthermore we will couple CEVSA and GLO-PEM (GLObal Production Efficiency Model), a production efficiency model driven entirely with satellite-derived variables, use high resolution remote sensing data, and improve some parameters and processes to strengthen the ability of CEVSA to quantify the carbon fluxes and spatio-temporal patterns in China´s terrestrial ecosystems. It is beneficial for evaluating the role of China´s terrestrial ecosystems in global carbon cycle and providing sufficient fundamental data for predicting future trajectory of climate changes.

关键词： China; terrestrial ecosystem; NPP; CEVSA; interannual variation; climate change