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Acta Botanica Sinica 2003, **45** (5): 552 - 560 http://www.chineseplantscience.com

Interannual Variation in Terrestrial Ecosystem Carbon Fluxes in China from 1981 to 1998 *

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Abstract: A dynamic biogeochemical model was used to estimate the responses of China's terrestrial net primary productivity (*NPP*), soil heterotrophic respiration (*HR*) and net ecosystem productivity (*NEP*) to changes in climate and atmospheric CO_2 from 1981 to 1998. Results show that China's total *NPP* varied between 2.89 and 3.37 Gt C/a and had an increasing trend by 0.32 % per year, *HR* varied between 2.89 and 3.21 Gt C/a and grew by 0.40 % per year, Annual *NEP* varied between - 0.32 and 0.25 Gt C but had no statistically significant interannual trend. The positive mean *NEP* indicates that China's terrestrial ecosystems were taking up carbon with a total carbon sequestration of 1.22 Gt C during the analysis period. The terrestrial *NEP* in China related to climate and atmospheric CO_2 increases accounted for about 10 % of the world's total and was similar to the level of the United States in the same period. The mean annual *NEP* for the analysis period was near to zero for most of the regions in China, but significantly positive *NEP* occurred in Northeast China Plain, the southeastern Xizang (Tibet) and Huang-Huai-Hai Plain, and negative *NEP* occurred in the Da Hinggan Mountains, Xiao Hinggan Mountains, Loess Plateau and Yunnan-Guizhou Plateau. China's climate at the time was warm and dry relative to other periods, so the estimated *NEP* is probably lower than the average level. China's terrestrial *NEP* may increase if climate becomes wetter but is likely to continue to decrease if the present warming and drying trend sustains.

Key words: China; net primary productivity (*NPP*); soil heterotrophic respiration (*HR*); net ecosystem productivity (*NEP*); climate change

Acting as a major source and sink of atmospheric carbon, terrestrial ecosystems regulate seasonal and interannual variations and affect the long-term changing trend in atmospheric CO_2 concentration. Since the Industrial Revolution, terrestrial ecosystems have absorbed about 20 % of CO_2 released from fossil fuel burning and land-use changes, and the uptake have increased substantially in the past decades (Bolin *et al*, 2000; Prentice *et al*, 2001). Despite extensive and intensive studies in the last decades, the magnitude, spatio-temporal variation, and underlying mechanisms of the terrestrial carbon sink remain uncertain because of the high heterogeneity, temporal variability, and mechanistic complexity in the processes and factors controlling ecosystem carbon cycle. These uncertainties are limiting our ability to predict the future atmospheric CO_2 concentration and climate change, and affect policy-making for mitigate the greenhouse effect. As a country with the third largest land area, China has diverse climate and ecological zones that include almost all types in the world, and some of which are unique. Therefore, quantification of the responses of China's terrestrial ecosystem carbon fluxes to climate change is of great significance to estimating the global terrestrial carbon sink. In the last decade, great progress has been made in the study of China's terrestrial ecosystem productivity and carbon storage (Zhou and Zhang, 1996; Fang *et al*, 1996; 2001). It has been estimated that the carbon storage in China's vegetation is about 6 Gt C, soil carbon storage is 92 - 186 Gt C, total net primany productivity (*NPP*) is 2 - 3 Gt C (Zhou and Zhang, 1996; Fang *et al*, 1996; 2001), annual carbon uptake by forest is 0.02 - 0.05 Gt C, and agricultural soil may take up 0.14 Gt C/a. However, few studies have been conducted to quantify the interannual variations and changing trend in China's terrestrial ecosystem carbon fluxes. Process-based ecosystem models describe mechanistic processes of ecosystem carbon cycle and their dynamic responses to changes in environmental conditions, and have been widely used in identifying and quantifying the terrestrial carbon sink (Melillo *et al*, 1993; Cao and Woodward, 1998a; Cramer *et al*, 2001). Modern ecosystem models are developed based on extensively tested eco-physiological mechanisms, 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 can realistically capture the spatio-temporal pattern in terrestrial carbon fluxes. More importantly, ecosystem modeling is an essential tool to project the future changes in ecosystem carbon fluxes. In this study, we estimated the dynamic responses of China's terrestrial ecosystem carbon fluxes to changes in climate and atmospheric CO_2 during

* Received: 2002-04-25 Accepted: 2003-01-08
Supported by the Major Scientific Program of Knowledge Innovation Project of the Institute of Geographic Sciences and Natural Resources Research, The Chinese Academy of Sciences (CXIOG-E01-02-04); the US National Aeronautics and Space Administration (NASA) Under the Contract NAG 5932.

the period 1981 - 1998 using the Carbon Exchange in the Vegetation-Soil-Atmosphere System (CEVSA) model (Cao and Woodward, 1998a; 1998b). With the simulation results, we analyzed the spatial distribution, interannual variations, and changing trend of China's terrestrial carbon fluxes and their correlations with climate variability.

1 Methodology

1.1 CEVSA model

Terrestrial ecosystem carbon cycle occurs through the processes of photosynthesis, autotrophic respiration, litter production, and heterotrophic respiration (*HR*) that 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 (Fig. 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 described in the following sections.

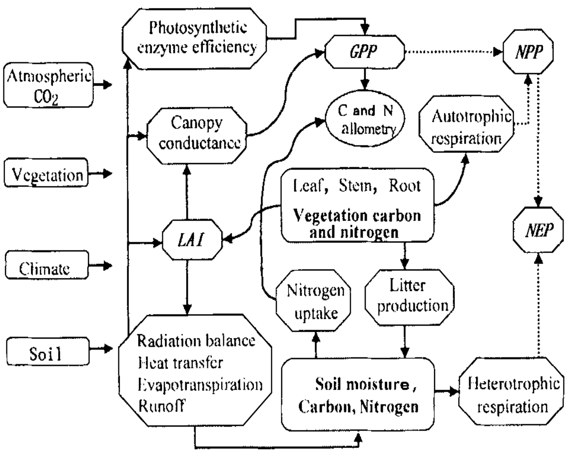

Fig. 1. A schematic representation of Carbon Exchange in the Vegetation-Soil-Atmosphere System (CEVSA) that was used in this study to estimate interannual variations in terrestrial ecosystem carbon fluxes and stocks.
GPP, gross primary productivity; *LAI*, leaf area index; *NEP*, net ecosystem productivity; *NPP*, net primary productivity.

1.1.1 Plant photosynthesis and NPP Plant photosynthesis depends on the CO_2 utilization efficiency of photosynthetic biochemical processes and CO_2 supply by diffusion through stomata into leaf intercellular spaces. The rate of plant CO_2 assimilation implied by biochemical processes (A_b) is (Collz *et al*, 1991)

$$A_b = min\{W_c, W_j, W_p\}(1 - 0.5P_o/\tau P_c) - R_d \quad (1)$$

where W_c represents the efficiency of photosynthetic enzyme system, specifically the carboxylating enzyme Rubisco, and is related with foliar nitrogen content. W_j is the limitation of electron transport to photosynthesis as a function of incident photosynthetically active radiation (*PAR*). W_p is the limitation of triose phosphate utilization to photosynthesis, representing the capacity of the leaf to utilize or export the product of photosynthesis. P_o and P_c are the internal partial pressure of O_2 and CO_2 respectively. τ is a factor depending upon temperature. R_d is the rate of respiration in light due to processes other than photorespiration.

Stomatal conductance controls the diffusion of CO_2 from the atmosphere into the intercellular air spaces and thus CO_2 supplys for photosynthesis. The rate of plant CO_2 assimilation implied by the stomatal conductance to CO_2 (A_d) is (Harley *et al*, 1992)

$$A_d = g_s(P_a - P_c)/160 \quad (2)$$

$$g_s = (g_o(T) + g_1(T)A\,R_h/P_a)\,k_g(w_s) \quad (3)$$

where g_s is stomatal conductance, and P_a is the partial pressure of atmospheric CO_2. g_o is the stomatal conductance when plant CO_2 assimilation is zero at the light compensation point, and g_l is an empirical sensitivity coefficient. A is the actual rate of plant CO_2 assimilation. R_h is relative humidity of the air surrounding the leaf. T is absolute temperature. $k_g(w_s)$ describes the response of stomatal conductance to soil water content (w_s).

The above equation shows that, in addition to being affected by many environmental factors, plant CO_2 assimilation and stomatal conductance interact with each other for keeping a balance between CO_2 utilization and supply in the intercellular air spaces. They can only be determined by iteratively solving the nonlinear equations that arises by setting A_d equal to A_b. In the calculations, the plant canopy is divided into layers, each of which has a unit of *LAI* and the rates of CO_2 assimilation and stomatal conductance of each layer are calculated separately. *LAI* is determined based on the conditions that the net CO_2 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).

1.1.2 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 (A_I) is allocated to leaves (C_L), stems (C_S) and roots (C_R) as:

$$A_I = C_L + C_S + C_R \quad (4)$$

C_L is calculated as follows:

$$C_L = LAI/S \quad (5)$$

where S is specific leaf area. According to Givnish (1986), a fraction of A_I is allocated to leaves (f) and is estimated as:

$$f = R_m / R_s + R_m \quad (6)$$

where R_m is the leaf mesophyll resistance to CO_2 uptake, and R_s is the stomatal resistance to water loss (Woodward *et al*, 1995). Based on the calculated f and C_L, C_R is given as:

$$C_R = C_L (1 - f) / f \quad (7)$$

C_s 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. Autotrophic respiration includes growth and maintenance respiration, which is affected by temperature, carbon storage, and photosynthetic rate (Woodward *et al*, 1995). The carbon in various plant organs is given a mean residence time with a statistical distribution (Lloyd and Farquhar, 1996), based on which the carbon storage in various plant organs and litter production are estimated. The seasonality of litter production is determined according to the phenology of various vegetation types, in which aboveground litter fall occurs at the end of the growing season in deciduous forests and seasonal grasses, in spring in a seasonal evergreen vegetation, and is spread evenly over the year in an evergreen vegetation. Root litter shedding was simulated in a similar way, except that root litter shedding is made to lag one month behind the aboveground litter fall (Box, 1988). *NPP* and the change of the carbon storage in the standing vegetation are

$$NPP = A_I - \sum R_i \quad (9)$$

$$dVGC / dt = AI - \sum R_i - \sum LT_i \quad (10)$$

where R_i and LT_i are, respectively, the autotrophic respiration and litter production of leaves, stems and roots.

1.1.3 Soil heterotrophic respiration (HR), soil carbon storage, and net ecosystem production (NEP) Litter entering soils is transformed into soil organic matter, and finally is decomposed into gaseous carbon products through microbial decomposition. CEVSA divides soil organic matter into pools of surface litter, root litter, microbes, and slow and passive carbon materials (Cao and Woodward, 1998b). All carbon transformations and decomposition of these pools were considered to be first-order rate reactions and each of them has a specific decay rate that is adjusted according to temperature, soil moisture, nitrogen availability, soil texture, and litter quality (lignin/nitrogen ratio). *HR* is determined as the sum of gaseous carbon loss in the microbial decomposition of various carbon pools:

$$HR = \sum SOMi\ K_i (1 - \varepsilon) \quad (11)$$

Where SOM_i and K_i are the carbon storage and decay rate respectively of various carbon pool. ε is the assimilation efficiency, i.e., the fraction of decomposed carbon that is incorporated in microbial tissue. The change in soil carbon storage is the difference between litter input and microbial respiratory loss:

$$dSOC / dt = LT - HR \quad (12)$$

1.1.4 Net ecosystem production (NEP) The difference between *NPP* and *HR*, defined as *NEP*, represents the net carbon uptake or release by ecosystems through biological activities:

$$NEP = NPP - HR \quad (13)$$

If there is no other disturbances, such as fire and harvest, *NEP* can be considered as the net carbon exchange flux between terrestrial ecosystems and atmosphere. A positive *NEP* indicates that the ecosystem is a carbon sink, negative *NEP* a carbon source.

2 Model Validation, Running and Data Sources

2.1 Model validation

CEVSA was 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). In addition, CEVSA model has been used at 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; 2002).

2.2 Model running and data sources

We run CEVSA with observation-based data sets of climate, atmospheric CO_2, and vegetation distribution to calculate the changes in *NPP*, *HR*, *NEP*, and the carbon stocks in vegetation and soils in the period 1981-1998. The climate data were supplied by the Climatic Research Unit, University of Norwich, U.K. that include monthly-mean values of temperature, precipitation, water vapor pressure, wet day frequency, diurnal temperature range, and sunshine duration with a spatial resolution of 0.5° (New *et al*, 2000). Monthly atmospheric CO_2

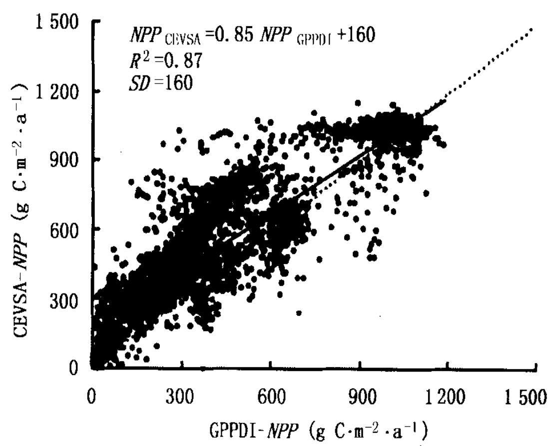

Fig. 2. Comparison between the estimated net primary productivity (*NPP*) with CEVSA and that from field measurements.
The measured *NPP* data for about 50 000.5° grid cells were derived from the International Geosphere-Biosphere Programme (IGBP) Global Primary Production Data Initiative (GPPDI) data set (Cramer *et al*, 2001).

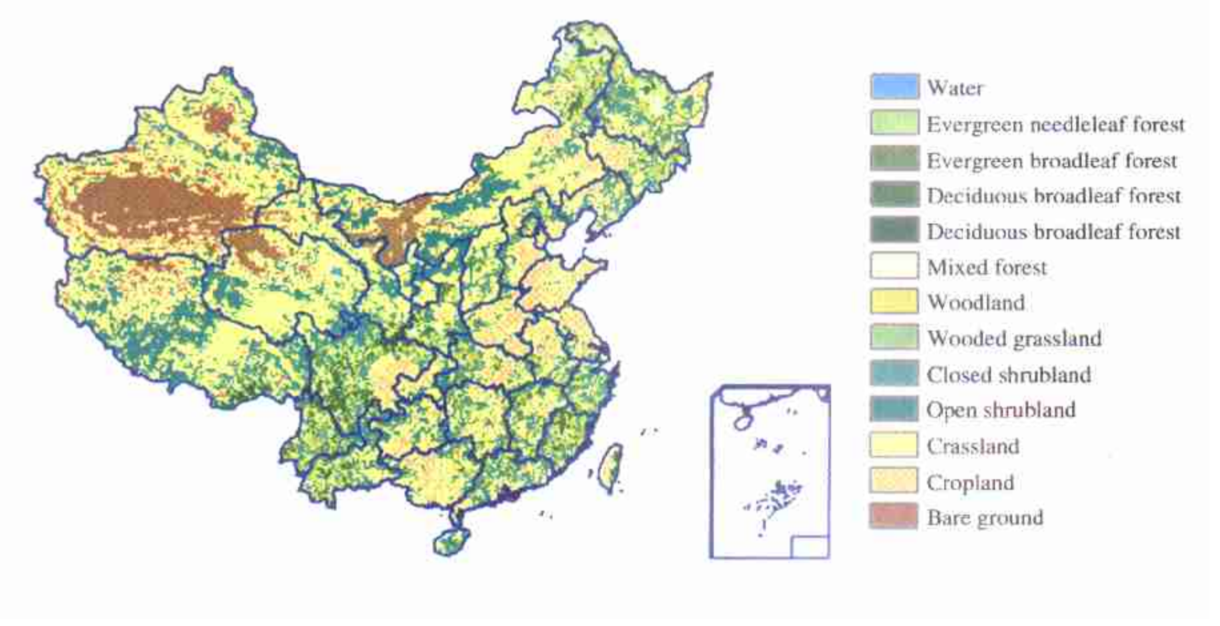

Fig. 3. The distribution of land cover types in China from data basedon remote sensing.

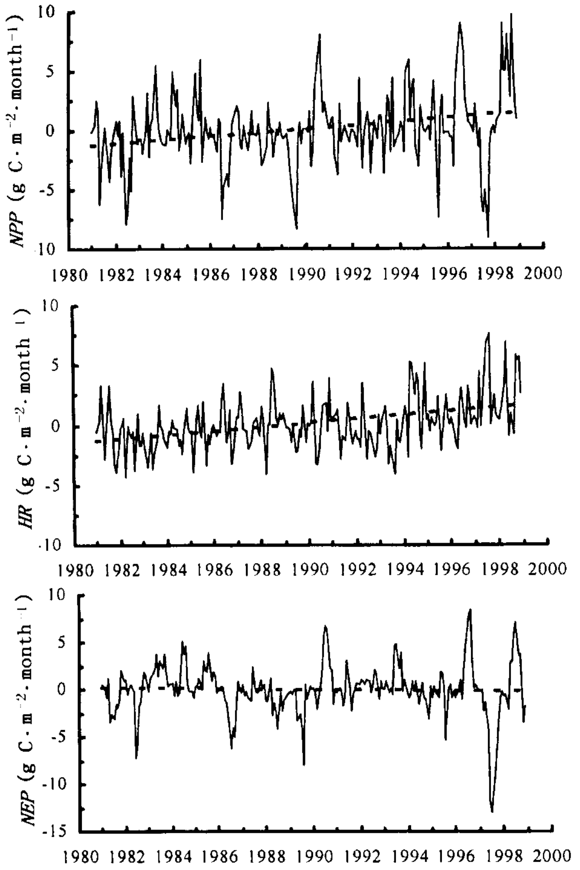

Fig. 4. Anomalies in nationally mean *NPP*, *HR*, and *NEP* as deviations of their values for a given month from the mean for that month in the period 1981 - 1998.
The dashed lines are the trend lines. Abbreviations are the some as in Fig. 1

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 that were classified using the National Oceanic and Atmospheric Administration National Aeronautics and Space Administrotion the Advancel Very High Resolution Roliometer (NOAA/NASA AVHRR) data at 1 km resolution (Fig. 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 CO_2. The run from 1951 to 1980 is for removing the artifacts from the assumption that ecosystems are equilibrium in the initialization run.

3 Results

3.1 Net primary productivity (NPP)

China's total terrestrial *NPP* we estimated to vary between 2.89 to 3.37 Gt C/a with a mean value of 3.09 Gt C/a. The interannual coefficient of variation was 4.3 %, and the fluctuating magnitude (the difference between the maximum and minimum annual *NPP*) was up to 0.48 Gt C, 15.6 % of the average value for the period 1981 - 1998 (Figs. 4, 5). *NPP* ranged from 40 g C · m^{-2} · a^{-1} for open shrubs to over 1 000 g C · m^{-2} · a^{-1} for evergreen broad-leaved forests, the nationally mean value was 340 g C · m^{-2} · a^{-1}. The *NPP* in Southwest and Southeast China accounted for two thirds of the nation's total, whereas North, Northeast and Northwest China contributed the remaining one third. Interannual variation in *NPP* was correlated positively with annual precipitation

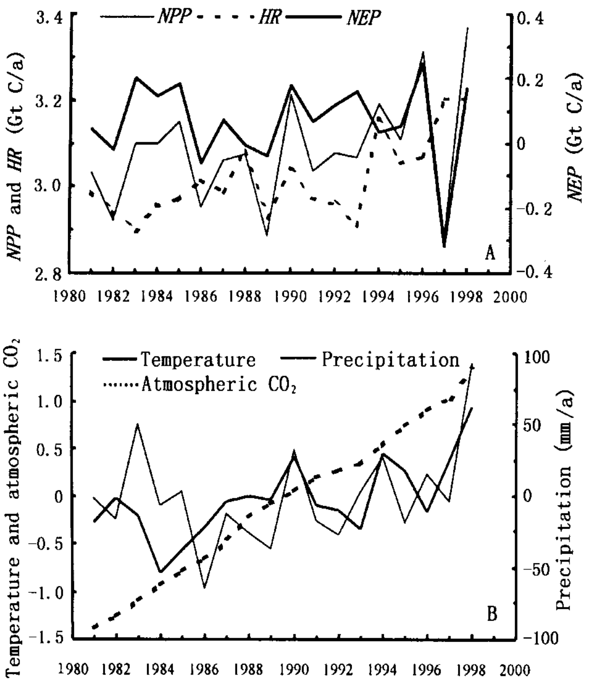

Fig.5. Changes in annual total *NPP*, *HR*, and *NEP* (A) and the anomalies in the mean temperature (℃), precipitation (mm per year), and atmospheric CO_2 concentration (Pa) (B) for the whole China.
Abbreviations are the same as in Fig.1.

($R^2 = 0.55$, $P < 0.01$). The correlation with temperature was not significant, but the change in temperature affected the response of *NPP* to precipitation. Warming appeared enhancing the *NPP* increase in wet years (e.g. 1990, 1994 and 1998) and the decreases in dry years (1982, 1986 and 1997). Reducing the impact of drought on soil moisture, cooling alleviated the decreases in *NPP* in dry years (e.g. 1984 and 1996, Fig.5).

The responses of *NPP* to climate variability varied between regions. *NPP* and precipitation correlated positively ($R^2 = 0.97$, $P < 0.01$) in Northwest and North China, almost every increase or decrease in precipitation caused the corresponding change in *NPP*. The large interannual variations in precipitation in these regions caused the coefficient of variation in *NPP* as high as 14.9 % and the interannual fluctuation magnitude reached 55.6 % of the mean value over the analysis period. Despite the cool climate, interannual variations in *NPP* in Northeast China also correlated clearly with precipitation ($R^2 = 0.85$, $P < 0.01$), due to the fast increase in temperature by 0.06 ℃ per year ($R^2 = 0.85$, $P < 0.01$), which increased evaporatranspiration and hence water availability. In Southeast China, annual *NPP* varied by 3.8 %, being correlated negatively with temperature ($R^2 = 0.17$, $P < 0.05$) but not with precipitation. In Southwest China, the interannual variation in *NPP* was only 1.9 %, but was correlated positively with both temperature ($R^2 = 0.53$, $P < 0.01$) and precipitation ($R^2 = 0.49$, $P < 0.01$).

The minimum and maximum *NPP* occurred, respectively, in 1997 and 1998. In 1997, *NPP* in Southeast and Southwest China increased with increases in precipitation, however the nationally mean *NPP* decreased by 14 % from the mean value as a consequence of warming and drought across North China. In that year, *NPP* in Northeast, North and Northwest China was 8 % - 24 % lower than the average value, because precipitation decreased by 12 % - 28 % and temperature increased by 0.5 - 1.2 ℃. The largest decrease in *NPP* occurred in Songnen Plain, Huang-Huai-Hai Plain, and Loess Plateau, where annual *NPP* decreased by 140 g C/m^2. In 1998, *NPP* was 9.4 % higher than the average value in the analysis period as both temperature and precipitation reached the highest on the records in the 20th century, and the increases occurred in almost all regions. In this year, precipitation increased by over 25 % in Northeast China Plain, North China Plain, eastern Xizang (Tibet), western Yunnan, the hilly areas of the southern China, and Xinjiang.

NPP had an increasing trend by 0.32 % per year during the analysis period ($R^2 = 0.21$, $P < 0.05$). The mean *NPP* in the later 1990s (1995 - 1998) was 4.1 % higher than that of the early 1980s (1981 - 1985). The *NPP* increases were mainly related to the increases in atmospheric CO_2 concentrations and precipitation. Experimental data indicate that each 1 ppmv increase in the atmospheric CO_2 concentration would enhance plant photosynthesis by about 0.20 % (Wullschleger *et al*, 1995; Curtis and Wang, 1998). With this rate, the increase in atmospheric CO_2 concentration by 27 ppmv (Keeling and Whorf, 1999) during the period 1981 - 1998 can increase *NPP* by 5.40 %, explaining most of the estimated 5.76 % by the present study. Meanwhile, the increases in precipitation in the later 1990s in some regions of North China, Xinjiang and Southwest China also helped to increase *NPP*. During the period 1981 - 1998, annual *NPP* increased in most regions of the country, of which the increases of more than 50 g C/m^2 occurred in Liaohe Plain, North China Plain, and the coastal areas of southern China. Because of warming and drought in the later 1990s, *NPP* decreased in the Loess Plateau, Da Hinggan Mountains, Xiao Hinggan Mountains, Sanjiang Plain and the Changbai Mountains (Fig.6).

3.2 Soil heterotrophic respiration (HR)

The annual total *HR* varied between 2.89 and 3.21 Gt C (Figs. 4, 5), the mean value was 3.02 Gt C/a, and had a similar spatial pattern as *NPP*. The coefficient of variations in annual *HR* was 3.1 % and varied by 0.31 Gt C interannually. Annual *HR* was correlated with temperature ($R^2 = 0.56$, $P < 0.01$), but was not with precipitation at the national scale. As expected, the highest and lowest *HR* occurred, respectively, in years with the highest (1990, 1994 and 1998) and lowest temperatures (1983, 1989 and 1993). The correlation of *HR* with temperature was positive in all regions but Southeast China, but the correlation with precipitation differed between regions. *HR* in Northwest and North China was not

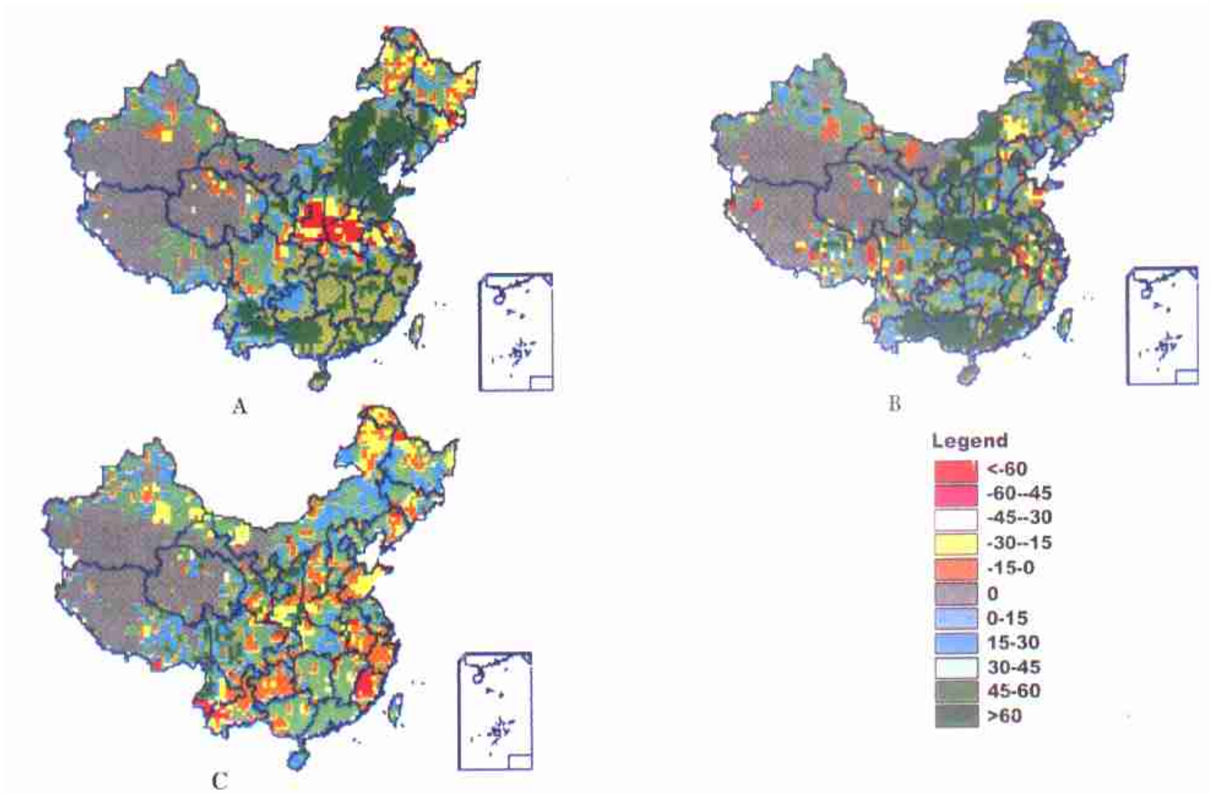

Fig. 6. Changes in *NPP* (A) and *HR* (B) from the earlier 1980s (1981 - 1985) to the later 1990s (1995 - 1998) and the mean *NEP* (C) for the period 1981 - 1998 ($g\ C \cdot m^{-2} \cdot s^{-1}$)
Abbreviations are the same as in Fig. 1.

statistically correlated with interannual variations in precipitation, but the limitation of water availability to changes in *HR* was evident. For instance, annual mean temperature in these regions increased by 1.5 - 2.0 ℃ during the period 1984 - 1990, however *HR* had no substantial increases because precipitation did not increase. In Southeast China, *HR* was negatively correlated with precipitation, it usually increased in dry years. In Southwest China, *HR* increased with the increases in precipitation.

HR increased markedly in 1997 and 1998 that were the warmest years in the 20th century (Fig. 6), however, the spatial pattern of the increases differed between the two years because 1997 was dry but 1998 the wettest year in the analysis period. In 1997, *HR* increased mainly in Nei Mongol, Loess Plateau and Songnen Plain, where temperature increased by 0.8 - 1.2 ℃, and precipitation decreased by 20 % - 30 %, whereas *HR* decreased in Yunnan and Xizang due to cooling and in Southeast China due to the increases in precipitation. In 1998, *HR* increased mainly in central and Southwest China but decreased *HR* in regions along the Great Wall and the Xiao Hinggan Mountains. As expected, *HR* decreased in cool years, such as 1983 and 1993, across the country, particularly in Northeast China, Loess Plateau, and Yunnan-Guizhou Plateau.

During the period 1981 - 1998, *HR* increased by 0.40 % per year ($R^2 = 0.45$, $P < 0.01$) with the increases in temperature by 0.04 ℃ pear year ($R^2 = 0.42$, $P < 0.01$). The total *HR* increased robustly from 2.94 Gt C/a in the earlier 1980s to 3.13 Gt C/a in the later 1990s. We estimated that an increase in temperature by 1 ℃ could cause the increases of 0.17 Gt C in China's total *HR*. Large increases in *HR* occurred in Northeast China Plain, Nei Mongol, Loess Plateau and the coastal areas of South China, where annual *HR* in the later 1990s is over 50 g C/m higher than in the earlier 1980s (Fig. 6).

3.3 Net ecosystem productivity (NEP)

During the period 1981 - 1998, China's total terrestrial *NEP* varied between - 0.32 and 0.25 Gt C/a with a mean value of 0.07 Gt C/a (Figs. 4, 5). The carbon storage increased by 0.84 Gt C in vegetation and 0.38 in soils, so the total carbon uptake was 1.22 Gt C during the analysis period. The map of the mean annual *NEP* (Fig. 6) shows that most parts of China was carbon balanced (Fig. 6), however, significant carbon uptake occurred in Northeast China Plain, the southeastern Xizang, and Huang-Huai-Hai Plain, and carbon releases occurred in Da Hinggan Mountains, Xiao Hinggan Mountains, Loess Plateau, Yunnan-Guizhou Plateau, the hilly regions in Shandong, Zhejiang and Fujian Provinces. During the period 1981 - 1998, *HR* had a higher growth rate than *NPP*, but *NEP* had no statistically significant decreasing trend because of the high interannual variability (Fig. 4). In most areas, the increases in *NPP* were counterbalanced by the increases in *HR*, so *NEP* had no much change. However, *NEP* decreased with decreases in *NPP* in the Loess Plateau, Da Hinggan Mountains, Xiao Hinggan Mountains, and Changbai Mountains.

As a residual between *NPP* and *HR*, *NEP* was one to two orders of magnitude lower, so the coefficient of variations of annual *NEP* was as high as 196 %, and the interannual magnitude was 0.56 Gt C, about eight times of the mean value for the period 1981 - 1998. Changes in *NPP* contributed mainly to the interannual variation in *NEP*, but *HR* played a major role in some years (Fig. 5). For example, a cooling-induced decrease in *HR* in the period 1991 - 1993 caused the increases in *NEP* despite decreases in *NPP*. The interannual variation in *NEP* was positively correlated with precipitation (R^2 = 0.26, $P < 0.05$), but its relationship with temperature was complicated. *NEP* was usually low in years with low temperature (e.g. 1983 - 1985 and 1991 - 1993), but the changes in warm years depended largely on precipitation. In 1997, *NPP* is the lowest and *HR* was the highest, so *NEP* reduced markedly, and the resulting carbon release was three times of the total carbon release in all other years. In this year, *NEP* was negative throughout the northern China (excluding Sanjiang Plain), of which North China Plain, Loess Plateau and Northeast China Plain had *NEP* below - 100 g C·m^{-2}·a^{-1}. In 1996, *NEP* was the highest due to the increases in *NPP* but decreases in *HR*. In this year, except in Northeast China and Fujian Province where severe drought occurred, *NEP* was positive in all other regions, particularly, *NEP* was high than 100 g C·m^{-2}·a^{-1} in North China Plain and Nei Mongol, where temperature decreased by 0.3 ℃ and precipitation increased by 28 %. In 1991 - 1993, although *NPP* decreased in North China and Northeast China with drought, *NEP* was high because of drastic declines in *HR* with cooling.

In the northern China, interannual variation in *NEP* generally agree with that in *NPP*, in contrast to, *HR* seemed playing an important role in the southern China. For example, the decreases of *NEP* in Southeast China in 1986, 1988 and 1994 were caused by a sharp rise of *HR*. In Southwest China, the interannual coefficient of variations in *HR* was 56 % higher than that of *NPP*, hence *HR* is contributed more to the changes in *NEP* than *NPP*. In this region, *NEP* increases in the earlier 1980s and 1990s (1982 - 1983, 1992 - 1993) and decreases in the later periods (1987 - 1988, 1997 - 1998) were caused mainly by the variations in *HR*, for example, although the *NPP* in 1998 was highest, but the *NEP* was the lowest because of substantial increases in *HR*.

4 Conclusions and Discussion

This study estimated that China's total *NPP* varied between 2.89 and 3.37 Gt C/a and an increasing trend by 0.32 % per year was superimposed on the large interannual variation. Total *HR* varied between 2.89 and 3.21 Gt C/a with a growth rate of 0.40 % per year. Annual *NEP* ranged from - 0.32 to 0.25 Gt C/a with a mean value of 0.07 Gt C/a, leading to carbon accumulation of 0.84 Gt C in vegetation and 0.38 Gt C in soil. Although *NEP* had no a clear interannual trend because of the high variability, the growth rate of *HR* was higher than that of *NPP*, implying that the capacity of the terrestrial carbon uptake may be undermined by the ongoing climate change. The mean *NEP* for the period 1981 - 1998 was near to zero in most regions of China, however, significantly positive *NEP* occurred in some areas of Northeast China Plain, southern Tibet and Huang-Huai-Hai Plain and negative *NEP* in Da Hinggan Mountains, Loess Plateau, Yunnan-Guizhou Plateau, and the southern hilly areas.

The total annual *NPP* estimated in the study is in middle of other estimates. For example, it was estimated as 2.65 Gt C/a by Sun *et al* using a radiation use efficiency model (Sun and Zhu, 2001), and 3.65 and 4.72 Gt C/a respectively by Xiao *et al* using Terrestrial Ecosystem Model (TEM) (Xiao *et al*, 1998) and Liu using TEPC (Terrestrial Ecosystem Production Process Model in China) (Liu *et al*, 2001). We compared of the carbon densities estimated with CEVSA model and those obtained with measured data. It is indicated that most of the vegetation and soil carbon densities simulated with CEVSA are in the range of the measured ones and in good agreement (Li *et al*, 2003). Nevertheless, the model estimates of *NPP*, *HR*, and *NEP* had to be validated with data from filed measurements. Currently, few observational data are available about the long-term changes in these ecosystems carbon fluxes, and the measurements of the carbon fluxes over large areas have not been conducted, but such research programs have been initialized in China. We will evaluate and validate the model estimates as the data become available. Although agreeing well with the results based on satellite observations, the estimates with process-based models have many uncertainties. For example, we used the climate and soil data at a spatial resolution of 0.5° and the model application in China have not been validated with observation data. We are currently developing the 0.1°, 10-d climate data to do more detailed analyses and are involved in the recently initialized flux measurements in China for model evaluation and validation.

The global terrestrial carbon sink in the past two decades ranged from 2.0 to 4.0 Gt C/a (Prentice *et al*, 2001; Bolin *et al*, 2000). A global study with CEVSA estimated that atmospheric CO_2 increases and climate change caused global *NEP* between - 0.64 and 1.68 Gt C/a with a mean of 0.62 Gt C/a during the period 1981 - 1998 (Cao *et al*, 2001), the mean value of other models' estimates is about 1.0 Gt C/a (Cramer *et al*, 2001). According to the estimate of this study, China's terrestrial carbon uptake in response to the changes in atmospheric CO_2 and climate accounts for 7 % - 10 % of the world's total and is equivalent to the level of the United States (0.08 Gt C/a) (Schimel *et al*, 2000). Atmospheric observations show that the global terrestrial carbon sink increased from 1.9 Gt C/a in the 1980s to 2.0 - 4.0 Gt C/a in the 1990s (Prentice *et al*, 2001). CEVSA estimated that global *NPP* increased by 0.3 %

and *NEP* from 0.3 Gt C/a in the 1980s to 1.1 Gt C/a in the 1990s (Cao *et al*, 2001). This study shows that the growth rate of China's terrestrial *NPP* in the past two decades was higher than the global average level, but *NEP* did not increased because of the warming-induced high increases in *HR*. Terrestrial ecosystem carbon uptake mainly occurred in boreal and temperate forests at northern middle and high latitudes (Prentice *et al*, 2001; Bolin *et al*, 2000), but there are not much these forests left in China, and the *NEP* of these remaining forests, such as in Da Hinggan Mountains and Xiao Hinggan Mountains and Changbai Mountains, decreased in the period 1981 - 1998 due to warming and decreased precipitation. A recent study indicated the carbon storage in China's forest increased in the past 20 years because of reforestation and afforestation (Fang *et al*, 2001), but our study did not consider the effect of the land-use changes.

The climate in China was warm and dry during the period 1981 - 1998 as the global mean temperature reached the highest and El Nino events was strongest on records in the same period (Folland *et al*, 2001). China's terrestrial mean temperature in the 1990s was highest in the 20th century, and strong warming occurred in the arid regions of the northern China. Precipitation in China, particularly in the North, has been declining since the 1960s, though had some increases in the late 1990s, it was still lower than that in the 1960s. For example, the precipitation in Nei Mongol, North and Southwest China in the 1990s was 5 % lower than the mean value of the 20th century. The results of study indicate that China's *NPP* decreases with drought and *HR* increases with warming. If the climate becomes wetter, China's terrestrial carbon uptake would increase, but if the current warming continues without significant increase in precipitation, China's terrestrial ecosystem could change from a weak carbon sink into a carbon source.

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(Managing editor: HAN Ya-Qin)

1981～2000 年中国陆地生态系统碳通量的年际变化

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摘要: 应用一个生物地球化学模型(CEVSA)估算了中国陆地净初级生产力(*NPP*)、土壤异养呼吸(*HR*)和净生态系统生产力(*NEP*)在1981～1998年期间对气候和大气CO_2浓度变化的动态响应。结果显示,全国*NPP*总量波动于2.89～3.37 Gt C/a之间,平均值为3.09 Gt C/a,年平均增长趋势约为0.32%。*HR*总量变化范围为2.89～3.21 Gt C/a,平均值为3.02 Gt C/a,年均增长0.40%。*NEP*总量变动于 -0.32和0.25 Gt C/a之间,在统计上没有明显的年际变化趋势。在研究时段内,年平均*NEP*约为0.07 Gt C/a,表明中国陆地生态系统在气候与大气CO_2浓度变化的条件下吸收了碳,为碳汇,总的吸收量为1.22 Gt C,约占全球碳吸收总量的10%,与同期内美国由大气CO_2和气候变化所产生的碳吸收量大致相当。尽管由于较高的年际变率,*NEP*在统计上没有明显的变化趋势,但*NPP*的增长率低于*HR*的增长率,说明在研究时段内,中国陆地生态系统的吸碳能力由于气候变化降低了。全国大多数地区年平均*NEP*接近零,明显的*NEP*正值区(即碳汇)出现在东北平原、西藏东南部和黄淮平原等地区,而大小兴安岭、黄土高原和云贵高原等地区*NEP*为负值(即碳源)。研究认为,1981～1998年期间中国气候温暖、干旱,因此估算的*NEP*可能低于其他时段。如果气候进入一个比较湿润的时期,碳吸收量可显著增加,但若当前干旱和暖化趋势以此为继,中国的*NEP*可能会变成一个负值。

关键词: 中国; 净初级生产力; 土壤异养呼吸; 净生态系统生产力; 气候变化

中图分类号: Q948.1 **文献标识码**: A **文章编号**: 0577-7496(2003)05-0552-09

收稿日期:2002-04-25 接收日期:2003-01-08

基金项目:中国科学院地理科学与资源研究所知识创新工程主干科学研究计划专题"中国陆地生态系统碳循环模式综合研究" (CXIOG-E01-02-04); the US National Aeronautics and Space Administration (NASA) Under the Contract NAG5932。

(责任编辑: 韩亚琴)