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Model of the Net Primary Productivity of Terrestrial Ecosystems in China and its Response to Climate Change

By

Y. R. ZHENG[1)], Z. X. XIE[2)], L. H. JIANG[1)], L. J. CHEN[3)], Y. J. YU[3)], G. S. ZHOU[1)] & H. SHIMIZU[3)]

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Summary

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The present study proposed to distinguish agricultural vegetation from natural vegetation when modelling net primary productivity (NPP), and developed a NPP model specifically for agricultural vegetation in China. The new model and the ZHOU & ZHANG model 1996 were then used to simulate NPP for agricultural land and natural ecosystems in China, respectively. The results showed that the overall accuracy improved when simulating the present NPP. As a general trend, NPP declined from southeast to northwest, with the lowest NPP in the Xinjiang Autonomous region. Except in extremely arid or extremely humid areas, agricultural NPP was usually lower than natural NPP, especially in northeastern China and the North China plain. The two models were also used to simulate NPP in China under three climatic change scenarios. The results demonstrated that if air temperature increased by 2°C and rainfall decreased by 20 %, both low NPP and high NPP area would decrease, resulting in an increase of medium NPP area. The other two scenarios, characterized by a temperature increase of 2°C, combined with precipitation increase of 20 % and with precipitation unchanged, showed a decrease in low NPP area and a increase in medium and high NPP area, however, the former resulted in a greater medium NPP increase. In conclusion, our approach supplied better predictions than those based on only a natural NPP model.

[1)] Institute of Botany, Chinese Academy of Sciences, No. 20 Nanxincun, Xiangshan, Beijing 100093, China. Fax: 86-10-82590429, e-mail: zhengyr@ibcas.ac.cn

[2)] Geosciences Department, Florida Atlantic University, Boca Raton, FL 33431, USA.

[3)] National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan.

Introduction

Modelling NPP has been a central focus over the last three decades. Global NPP modelling has evolved from simple linear regressions between NPP and climate variables to sophisticated simulations of interactions among multiple environmental factors, resulting from an improved understanding of terrestrial ecosystems. Currently, many established models could estimate the NPP of various ecosystems directly or indirectly, by considering either biogeographical or biogeochemical processes or both of them (CRAMER & FIELD 1999). However, it was not unexpected that no two modelling methods could give an identical result (CRAMER & FIELD 1999).

The terrestrial ecosystems of China occupy approximately 9,600.000 km^2, with one of the largest ecosystem diversity in the world. Thus, the functional and structural changes of the Chinese terrestrial ecosystems, driven by both natural and socio-economic forces, are important issues of global change studies (GAO & al. 2000). Some measurements and simulations of NPP have been conducted in China in the past decade, e.g., natural vegetation NPP estimation by CHIKUGO model (ZHANG 1993) and that by ZHOU & ZHANG 1996 model, simulation of regional vegetation dynamics using remote sensing data (GAO & al. 2000), simulation of NPP in China by BIOME3 (NI & al. 2000), estimation of biomass and productivity of natural vegetation in Tibet (LUO & al. 2002), the study of agricultural water cycle and agricultural production (TAO & al. 2003), and so on. However, it remains a challenge to reach an accurate NPP estimate in China for various reasons stated previously. Furthermore, previous studies on primary production in China concentrated on natural vegetation response to global climate change, whereas no research has attempted to distinguish the apparently different NPP response of agricultural vegetation from that of natural vegetation (ZHOU & ZHANG 1996). China has one of the longest agricultural histories in the world. Currently agricultural land still accounts for 18.84 % of the total terrestrial area in China, based on a vegetation map at 1:4,000.000 scales (HOU & al. 1982). Given the obvious differences in NPP responses between natural and agricultural vegetation and the important socio-economic role of agriculture in China, it is not only beneficial, but also, critical to separate agricultural vegetation from natural one in order to accurately estimate NPP of terrestrial ecosystems in China.

To take into account the fundamental differences between natural and agricultural ecosystems, a new NPP model was developed specifically for agricultural vegetation in China, and then the new model and the ZHOU & ZHANG model 1996 were used to estimate NPP for agricultural and natural ecosystems separately for present conditions, as well as under the three climate change scenarios.

Material and Methods

Climate and observed agricultural NPP data

The data used for the agricultural NPP model development and validation included monthly mean air temperature, monthly total precipitation, monthly mean air humidity, monthly mean wind speed, monthly mean sunshine fraction and observed agricultural NPP data from 27 provinces in China; all averaged between 1951 and 1999 (with 8 replicates for the agricultural NPP data).

Another set of climate data was used to model current NPP distribution in China and its dynamics under different global climate change scenarios. They included monthly mean air temperature and monthly total precipitation of 1473 weather stations in China, from 1951 to 1999. These data were used to calculate annual mean precipitation and biotemperature, which were converted into raster format, with 864 rows and 1008 columns, for use in NPP model simulation.

Climate change scenarios

We followed the scenario of GAO & al. 2000 and TANG & al. 2000, but considered three possible precipitation changes. The three climate change scenarios discussed were: (1) mean annual temperature increases by 2°C and annual precipitation increases by 20 %; (2) mean annual temperature increases by 2°C and annual precipitation decreases by 20 %; (3) mean annual temperature increases by 2°C and annual precipitation remains unchanged.

Vegetation data

The vegetation map was digitized from the "vegetation map of the People's republic of China", at 1:4,000,000 scales (HOU & al. 1982). The vegetation classes were grouped into two broad categories, natural vegetation and agricultural land. Only croplands were regarded as agricultural vegetation, while other vegetation including artificial vegetation such as artificial forest were grouped into "natural" vegetation. The map was converted to raster format with 864 rows and 1008 columns.

NPP model for natural vegetation

The ZHOU & ZHANG model 1996 was used to estimate natural vegetation *NPP* (Eq. (1)).

$$NPP = RDI \cdot \frac{rR_n(r^2 + R_n^2 + rR_n)}{(R_n + r)(R_n^2 + r^2)} \cdot Exp(-\sqrt{9.87 + 6.25 \cdot RDI}) \qquad (1),$$

where R_n is annual net radiation (mm), r is annual precipitation (mm), *RDI* is radiative dryness index and *NPP* is net primary productivity of natural vegetation (tons ha^{-1} yr^{-1}).

New *NPP* model for agricultural vegetation

As the first step to establish an effective NPP model for agricultural vegetation, we tested whether the ZHOU & ZHANG model (Eq. (1)) and the CHIKUGO model (Eq. (2)) were sufficient to simulate NPP of agricultural land in 27 provinces of China and compared the results with gathered agricultural NPP data. The CHIKUGO model was described by Eq. (2).

$$NPP = 0.29Exp(-0.216(RDI)^2) \cdot R_n \qquad (2),$$

where R_n is annual net radiation (Kcal cm^{-2} yr^{-1}). To calculate NPP with Eq. (1) and (2), R_n and *RDI* need to be derived, by Eq. (3) and (4).

$$R_n = RDI \cdot r \qquad (3),$$

where *RDI* could be calculated by Eq. (4) based on ZHANG (1993),

$$RDI = (0.629 + 0.237PER - 0.00313PER^2)^2 \qquad (4),$$

where *PER* is evapotranspiration rate, and could be calculated by Eq. (5),

$$PER = PET / r \qquad (5),$$

where *PET* (mm) is calculated by PENMAN's equation (ROSENBERG & al. 1983).

The results showed that both the ZHOU & ZHANG model and the CHIKUGO model were not good enough to estimate the real agricultural NPP. Therefore, it was necessary to develop a new model to estimate agricultural NPP in China. Our new model building process was detailed below.

First, according to UCHIJIMA & SEINO 1985, the ratio of plant productivity and evapotranspiration was a function of *RDI*, as could be represented by Eq. (6).

$$\frac{NPP}{AE} = f_n(RDI) \qquad (6),$$

where AE is actual evapotranspiration (mm). AE could be calculated by Eq. (7), which was developed by ZHOU & ZHANG 1996.

$$AE = \frac{rR_n(r^2 + R_n^2 + rR_n)}{(R_n + r)(R_n^2 + r^2)} \qquad (7).$$

The function in Eq. (6) is established through regression analysis, with the correlation coefficient being 0.92 ($P<0.001$). The subset of data used in regression included about two-thirds of the whole dataset (19 of 27 provinces), and they were randomly selected by casting points on province map of China. The resulted empirical regression equation is shown in Eq. (8).

$$\frac{LnNPP}{AE} = 0.0015RDI + 0.0013 \qquad (8),$$

where Ln means natural logarithm. Together with Eq. (7), an agricultural NPP model is established as Eq. (9).

$$NPP = Exp(\frac{rR_n(r^2 + R_n^2 + rR_n)}{(R_n + r)(R_n^2 + r^2)} \cdot (0.0015RDI + 0.0013)) \qquad (9).$$

Validity of new agricultural NPP model

The new agricultural NPP model was validated with the measured agricultural NPP of the other 8 provinces in China, the remaining subset of data not used for deriving the new agricultural NPP model. Validation results were shown in Fig. 1. It illustrated that the modelled NPP values by the new agricultural NPP model were in good agreement with measured data ($t=-1.03$, $p>0.05$, $df=7$), while modelled values by the CHIKUGO model and the ZHOU & ZHANG model deviated by a large margin ($t=-4.91$, $P<0.01$ and $t=-6.71$, $P<0.01$, $df=7$, respectively). Compared with 1:1 line, the intercept and slope in the regression line for the new agricultural NPP model were much closer to 0 and 1 than those by the CHIKUGO model and the ZHOU & ZHANG model (Fig. 1). This not only demonstrated the validity of using our new agricultural NPP model to calculate the agricultural NPP in China, but also further confirmed our concern that natural vegetation NPP models were not sufficient to estimate agricultural NPP.

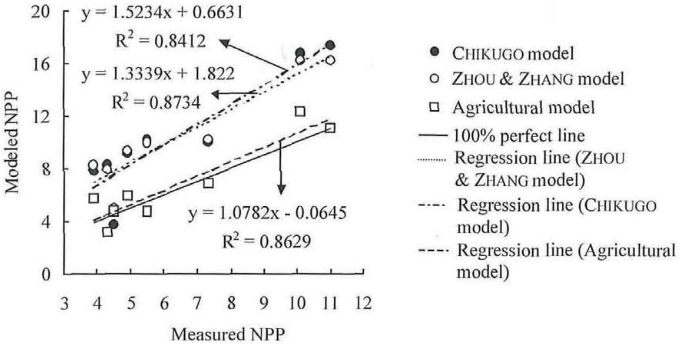

Fig. 1. Comparison of modelled net primary productivity (NPP) by the CHIKUGO model, the ZHOU & ZHANG model, the new agricultural model and measured agricultural NPP of 8 provinces of total 27 provinces in China. The unit for NPP is "tons ha^{-1} yr^{-1}".

Parameterizations of model

As shown in previous equations (Eq. (1) - (9)), many climate variables were needed to calculate R_n, however, not all of them were readily available in every part of China. Fortunately, this parameter could be estimated from available data. According to ZHANG 1993,

$$PET = BT \cdot 58.93 \qquad (10),$$

where BT is yearly mean biological temperature (°C) and could be calculated by Eq. (11):

$$BT = \sum t / 12 \qquad (11),$$

where t is mean monthly temperature (°C) with the condition that t<30°C and t>0°C. Thus, R_n could be calculated using Eq. (3), (4), (5), (10) and (11).

Up until now, every parameter in Eq. (1) and (9) could be derived from yearly biological temperature and total annual precipitation, both of which are available. We are now able to estimate NPP of terrestrial ecosystem in China, by separately calculating natural and agricultural vegetation NPP using natural NPP model (Eq. (1)) and agricultural NPP model (Eq. (9)), respectively.

Results and Discussion

Spatial patterns of NPP under contemporary climate

As illustrated in Fig. 2, the NPP of current terrestrial ecosystems in China showed a decreasing trend from the southeast to the northwest and formed obvious stripe zones. The stripe-zone distribution was most noticeable in the central part, with the stripes extending from the northeast to the southwest. In comparison, this stripe-zone distribution was much weaker in south China.

It also showed that, except in extreme arid and humid areas, agricultural NPP was lower than natural NPP. This was especially true in northeastern China and North China plains. It might imply the possibility of increasing crop productivity and yields close to natural vegetation NPP, relieving the heavy burden of feeding the enormous population of China with the limited arable lands.

To have a clear big picture of the NPP distribution, we further reclassified the NPP into three groups: low, medium and high (Table 1). At present, areas with low, medium and high NPP were mainly distributed in arid area, semi-arid and sub-humid arid area, and humid area in China, respectively.

Table 1. Ratio of net primary productivity (tons ha^{-1} yr^{-1}) of terrestrial ecosystem in different categories under different scenarios of climate change compared with that at present time in China. "T" and "r" represent annual mean temperature and annual mean precipitation, respectively.

NPP categories	Present time	T +2°C, no change of precipitation	T +2°C, r +20 %	T +2°C, r -20 %
Low (1-3)	42.5	35.9	30.3	42.3
Medium (3-10)	44.7	49.5	53.2	45.8
High (>10)	12.9	14.6	16.6	12.0

Potential response of NPP to future climate change scenarios

Compared with current conditions as shown in Fig. 2, when temperature increased by 2°C with precipitation remaining unchanged, low NPP area would decrease because some low NPP regions would produce medium NPP in Tibetan plateau. NPP increase of current medium NPP regions in southern China would lead to increase of high NPP area. The net effect would result in increase of medium NPP area.

If temperature increased by 2°C and precipitation increased by 20 %, low NPP area would decrease dramatically due to a significant increase of NPP in arid area, especially in the Northern part of Xinjiang Ugar Autonomous Region. Together with the increase of NPP in Northeast and North China Plain, medium NPP area and high NPP area would increase.

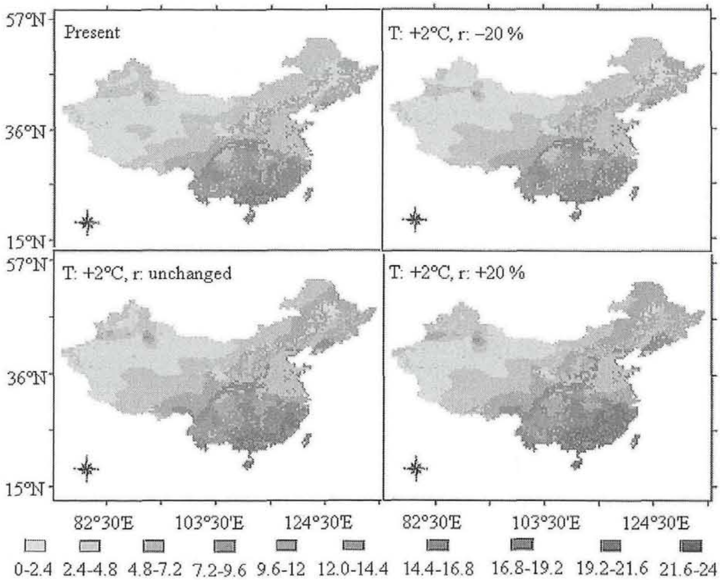

Fig. 2. Net primary productivity (tons ha^{-1} yr^{-1}) of terrestrial ecosystem in China at present time and under global change. "T" and "r" represented annual mean temperature and annual mean precipitation, respectively.

Based on above results, increasing temperature by 2°C with precipitation increasing 20 % or no change would induce an increase of NPP over China. In general, an increase in precipitation would improve the growth conditions for most vegetation and thus increased their productivity because a precipitation increase might reduce soil water stress and allowed a large proportion of assimilation to be allocated to green parts of plants. The precipitation increase might impose much more profound impacts on vegetation in northern than in southern China, as northern China currently has a much more limited water supply (GAO & al. 2000). Our simulations indicated that an increase of precipitation by 20 % might greatly improve soil water conditions in arid, semi-arid and sub-humid areas, and would result in dramatic NPP increase because the three types of areas together occupied a very large portion in China (FENG & al. 2001).

When a precipitation increase of 20 % was combined with temperature increase of 2°C, it would increase NPP in Tibet and northeast China, thus inducing a large increase of NPP. If only temperature increased 2°C, NPP would increase in northeast China, Tibet, southern China and the mountain area. However, because temperature increase would strengthen water stress in northern and especially northwestern China, NPP increase would be smaller than that under the scenario of a temperature increase by 2°C together with a precipitation increase by 20 %.

If temperature increased by 2°C but precipitation deceased by 20 %, some current high NPP regions would turn into medium NPP regions. Low NPP area would decrease a little after some was converted into medium NPP regions. Medium NPP area therefore would be increased. All of these might result in NPP decreases over China, because it would increase soil water stress in all northern China and parts of southern China.

In summary, our study predicted that heterogeneous NPP responses to climate change would happen in different parts of China. This conclusion might be closer to reality than those by some previous studies. In one study, GAO & al. 2000 argued that temperature increase would impose negative effects on most vegetation and consequently reduced their primary productivity by enhancing water stress, and the negative effects would be stronger in northern than in southern China. In another study, NI & al. 2000 predicted that NPP might increase with higher CO_2 concentration because of warm summers and longer growing seasons.

Although many climate change scenarios have been generated by different global circulation models (GCMs), no known GCM model has been specifically developed to target climate changes in China, which were spatially heterogeneous and very complex according to long-term observed climate data (SHANG & al. 2001). In the future, a special GCM model for China should be developed to warrant more accurate estimation of NPP responses.

Finally, many models have been used to simulate global NPP (CRAMER & al. 1999). There were also studies applying global NPP models for China, e.g. NI & al. 2000 used a biogeochemical, process-based equilibrium terrestrial biosphere model (BIOME3) to predict the NPP change of China. However, these models were developed for a global scale and might not supply sufficient details, although a quantitative pattern and its changes under global climate change by these models could still give us a framework of NPP change (NI & al. 2000). The present study used natural and agricultural models developed specially for China and was able to give much more detailed information for NPP change. The new agricultural NPP model adopted a linear regression modelling approach, because in a developing country like China, a mechanism-model was still difficult to build for various reasons and a simple correlation model might still be a better alternative (YATES & al. 2000). Moreover, the simulation results of the new model could not only present general NPP spatial patterns and changes, but also show profound information, such as whether agriculture NPP was above or below natural NPP in a specific region. The later information might help to make a better use of agricultural land by improving agricultural activities in a particular region if the current agricultural

NPP was less than certain portions of natural NPP.

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