Impact of future climate change on terrestrial ecosystems in China

Shaohong Wu,[a,b]* Yunhe Yin,[a] Dongsheng Zhao,[a] Mei Huang,[a] Xuemei Shao[a,b]
and Erfu Dai[a]

[a] *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[b] *Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China*

ABSTRACT: The impact of future climate change on terrestrial ecosystem was projected by the atmospheric-vegetation interaction model (AVIM2) over China at four warmer levels of 1, 2, 3 and 4 °C. Future climate data were projected by regional climate model from the Hadley Centre under Special Report on Emissions Scenarios (SRES) B2 scenario. The results show that, as projected temperature increases, the average net primary productivity (NPP) is likely to decrease in China as a whole. The Tibetan Plateau is the only ecoregion with increasing NPP as the climate becomes warmer. The terrestrial ecosystem NPP in China would be impacted as: 1 °C warmer, favourable or adverse impact on ecosystem would be equivalent with regional variation; 2 °C warmer, slight adverse impact would be significant; 3 °C warmer, moderate adverse impact would take priority and 4 °C warmer, moderate adverse impact regions would increase significantly. But overall, only a small part of the ecosystems are expected to be over moderately impacted. Areas impacted over moderately are likely to be enlarged in the same distributing pattern as temperature increases. The northwest arid region is expected to be the most vulnerable ecoregion. Copyright © 2009 Royal Meteorological Society

1. Introduction

Impact of climate change has been more and more significant. The recent Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has reported a world average surface temperature rise by about 0.74 °C over the past 100 years (1906–2005). The global mean surface temperature was projected to be likely to increase by 1.1–6.4 °C by the year 2100. Climate change, one of the severe challenges for human beings, has exerted great influences on ecosystems and socio-economic systems. The global observed evidence shows that the recent warming is strongly affecting terrestrial ecosystems, including such changes as the earlier timing of spring events and poleward and upward shifts in ranges in plant and animal species (IPCC, 2007). As for China, surface air temperature has increased by 0.5–0.8 °C and precipitation has large regional variation, but no significant trend in the last 100 years. The future surface air temperature will increase continually and precipitation will have unequal increasing trend in the 21st century (Taskforce on China's National Assessment Report on Climate Change, 2007).

Net primary productivity (NPP) is the rate of accumulation of carbon after losses from plant respiration and other metabolic processes in maintaining the plant's living systems are taken into account (Lieth and Whittaker, 1975). NPP is not only an important index to describe the structure, function and carrying capacity of terrestrial ecosystems but also the basis for understanding carbon cycle over land surface under climate change. Changes in terrestrial ecosystem NPP reflect climatic, ecological, geochemical and human influences on the biosphere (Nemani, 2003). Impact of climate changes on ecosystems mainly embodies carbon sequestration capacity of the ecosystems, and NPP is an important indicator to describe accumulation of carbon. Therefore, simulating future changes in NPP over large regions is pivotal for impact assessment to reduce climate change risk and for sustainable human use of the biosphere in the future.

Conclusions on the effect of climate change on global NPP are inconsistent. Terrestrial ecosystem NPP is sensitive to climate change. The NPP could both increase and decrease under future climate scenario (Melillo *et al.*, 1993; Anthony *et al.*, 1997; Cao and Woodward, 1998; White *et al.*, 1999; Woodward and Lomas, 2004; Cao *et al.*, 2005). Increase or decrease depends on types of vegetation, degree of climate changes and the changes in disturbance regimes associated with them (IPCC, 2001). For example, terrestrial ecosystem NPP in China would

* Correspondence to: Shaohong Wu, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11 A, Datun Road, Anwai, Beijing 100101, China.
E-mail: wush@igsnrr.ac.cn

increase due to climate change and elevated CO_2 concentration (Zhou and Zhang, 1996; Pan *et al.*, 2001; Fang *et al.*, 2003). If taking climate change into account only without considering CO_2 fertilizing effect in plants, the average forests NPP might reduce in China during 2091–2100 (Ju *et al.*, 2007). The productivity of forest would increase by 1–10% and more significant in higher latitude regions in China (Taskforce on China's National Assessment Report on Climate Change, 2007). China's vegetation NPP increased significantly in humid regions and less in arid and semi-arid regions (Cao *et al.*, 2003). NPP of most steppes in China will decrease by 15–20% and NPP of woodland, shrublands and desert grasslands will increase by 20–115% using a regional model with elevated CO_2, a 20% increase in precipitation and a 4 °C increase in temperature (Gao and Yu, 1998).

United Nations Framework Convention on Climate Change (UNFCCC) clarified that the ultimate objective of this convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner (UNFCCC, 1992). An important issue in the objective of UNFCCC is to what extent is the level of dangerous climate change and when reaches the dangerous level.

There have been studies focussing on dangerous climate change level on terrestrial ecosystems. Some studies indicated that if average global surface temperature rises by more than 2 °C above pre-industrial level, the risks to human societies and ecosystems will grow significantly and cause substantial agricultural losses and irreversible damage to important terrestrial ecosystems (International Climate Change Taskforce, 2005). Beyond 2 °C warming, the risk of large-scale human development setbacks and irreversible ecological catastrophes will increase sharply (United Nations Development Programme, 2007). According to IPCC AR4 (the Fourth Assessment Report of the Intergovernmental Panel on Climate Change), there is medium confidence that approximately 20–30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5–2.5 °C over the 1980–1999 levels. Confidence has increased that a 1–2 °C increase in global mean temperature above the 1990 levels (about 1.5–2.5 °C above pre-industrial) poses significant risks to many unique and threatened systems including many biodiversity hotspots (IPCC, 2007).

Although some dangerous climate change levels for certain ecosystems were detected, they were mostly deducted qualitatively. Moreover, there were inconsistent conclusions about the impact on natural ecosystems under

dangerous level of climate change, not to mention the difference of impacts under varied warmer levels.

In this paper, the impacts of climate change on terrestrial ecosystem NPP were compared under four warmer levels of 1, 2, 3 and 4 °C over China during the 21st century. The sensitivity of climatic factors, such as temperature, precipitation and moisture condition were also analysed. The results could be used as scientific basis for determining dangerous climate change level to plan proper greenhouse gas emission and for detecting vulnerable ecosystems.

2. Data and methods

2.1. Data

Future climate change data were provided by the research group of the Institute of Environment and Sustainable Development in Agriculture, the Chinese Academy of Agricultural Sciences (CAAS). Based on climate scenarios of SRES (Special Report on Emissions Scenarios) (Nakicenovic *et al.*, 2000), the group provided future socio-economic scenarios and predicted future climate change of 21st century in China according to the PRECIS (Providing Regional Climates for Impacts Studies) system (Jones *et al.*, 2004), which was introduced to China from the Hadley Centre in 2003. HadRM3 (the Hadley Centre Regional Climate Model Version 3) covers all important atmospheric and terrestrial physical processes with resolution of 50 km × 50 km at level direction (Met Office, 2002). PRECIS has been validated to have strong ability of simulating seasonal terrestrial climate change in China (Xu, 2004; Xu and Jones, 2004).

Projected climatic data from 1961 to 2100 were used in this study including the maximum, minimum and average temperatures, precipitation, relative humidity, wind speed and net solar radiation. The 5-year smoothing average of climate data was used to reduce data noise.

According to China's national mid-to-long term development plans, by 2050, per capita gross domestic product (GDP) would hit US $10 000, the total population rise to 1.54–1.58 billion, and the total consumption of primary energy would reach 3.9–4.9 Gt of coal equivalent. This projection is very close to the IPCC SRES B2 scenario (mid-low emissions scenario), the pathway for regional sustainable development (Lin *et al.*, 2007). Therefore, IPCC SRES B2 scenario was used in this paper to describe future impact on ecosystem NPP over China.

The vegetation of terrestrial ecosystems in China was grouped into 14 types: evergreen coniferous forest, evergreen broad-leaved forest, deciduous coniferous forest, deciduous broad-leaved forest, mixed forest, woody savannas, grasslands, alpine steppe, closed shrub lands, open shrub lands, croplands, cropland/natural vegetation mosaic, desert steppe, barren or sparsely vegetated land (Zhang *et al.*, 2004).

2.2. Methods

Future terrestrial ecosystem NPP was simulated by the atmospheric-vegetation interaction model (AVIM2) over China. AVIM2 is a dynamic terrestrial biosphere model with independent intellectual property and international recognition (Ji and Yu, 1999). AVIM2 model consists of three sub-models: terrestrial physical module of soil-vegetation-atmosphere transformation (SVAT), vegetation physiological growth module and soil organic matter (SOM) module. The SVAT module simulates the exchange of energy, water vapour and momentum between the surface, the vegetation canopies and the atmosphere. NPP is the residue of gross canopy photosynthesis minus maintenance and growth respiration. The three sub-modules are fully coupled in AVIM2 and the interchange of atmosphere, vegetation and soil is based on dynamic and inner coordinated mutual procession. The climatic variations in AVIM2 will influence both soil condition and vegetation growth. At the same time, the changes in soil condition have effects on both vegetation growth and transformation and decomposition of soil organic carbon.

The time step of input data for physical sub-model is every 30 min, and time steps of vegetation physiological and soil organic carbon sub-model are every 1 h and 1 day, respectively. The ecosystem NPP and carbon dioxide flux between vegetation and atmosphere have been simulated by the AVIM2 model which brought satisfied results (Ji and Yu, 1999; Lv and Ji, 2002; Ji *et al.*, 2005).

China is characterized by a broad range of climates from tropical to cold temperate and from humid to arid with diverse ecosystems. The macro distribution of ecosystems forms ecoregions with unique characteristics (Table I). Impacts of climate change on different ecoregions are various. Therefore, it is more reasonable to analyse the impact of climate change on ecosystems based on ecoregions. The distribution of ecoregions in China is shown in Figure 1.

The macro scale geographical distribution of ecoregions is mainly influenced by climate. The climate condition is indicated mainly by two variables including the
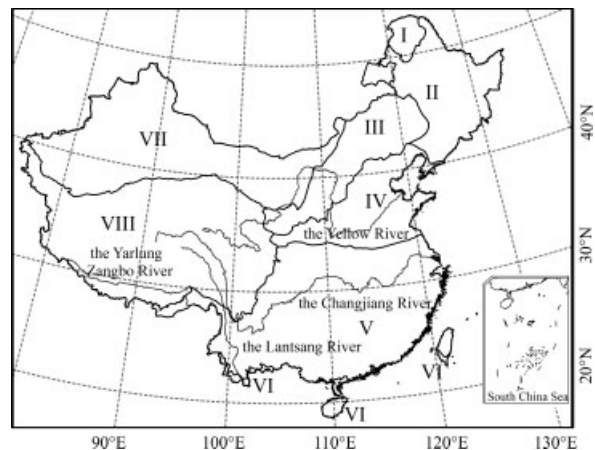

Figure 1. The distribution of ecoregions in China.

number of days of the accumulated temperature $>10\,°C$ (D) and aridity index (I_a) (Table I). Aridity index is calculated by the ratio of potential evapotranspiration (ET_o) to precipitation (P). In general, ET_o reflects the maximum water demand of environment for keeping water balance and P reflects water supply over large regions. Currently, as it is difficult to obtain observed ET_o over large regions, ET_o is often simulated by models. The Penman-Monteith model suggested by the Food and Agricultural Organization (FAO) in 1998 has been used in both arid and humid environment (Allen *et al.*, 1998). Therefore, the Penman-Monteith model was used to simulate ET_o over China in this study.

According to the relationship between changes in NPP and the impact degree of future climate change on natural ecosystems (Wu *et al.*, 2006), if the absolute change in NPP is $<40\%$, the impact degree is slight; if it is $40–60\%$, the impact degree is moderate; if it is $60–80\%$, it is severe and if it is over 80%, it is extremely severe.

3. Results

3.1. Future climate change at different warmer levels over China

Terrestrial land surface temperature is projected to increase by about $1\,°C$ in 2010, $2\,°C$ in 2038, $3\,°C$ in

Table I. Ecoregion and representative typical natural vegetation and climatic index.

Serial	Ecoregion	Typical natural ecosystem	Typical climatic index	
			Days of accumulated temperature $>10\,°C$	Aridity index
I	Cold temperate humid region	Deciduous coniferous forest	<100	<1
II	Temperate humid/sub-humid region	Broad-leaved and coniferous forest, forest steppe	$100–170$	<1.5
III	North semi-arid region	Steppe	$100–220$	$1.5–4$
IV	Warm temperate humid/sub-humid region	Deciduous broad-leaved forest	$171–220$	<1.5
V	Sub-tropical humid region	Evergreen broad-leaved forest	$221–365$	<1
VI	Tropical humid region	Seasonal rainforest and rainforest	365	<1
VII	Northwest arid region	Desert	$100–220$	>4
VIII	Tibetan Plateau region	Alpine shrub meadow, alpine steppe, alpine desert	<180	

2068 and 4 °C in 2098 relative to the baseline period (1961–1990). At different warmer levels of 1, 2, 3 and 4 °C, climatic factors including P, D and ET_o are likely to increase relative to the baseline period. Precipitation is projected to increase by 5.69% at 1 °C warmer level, then decrease at 2 °C warmer; however, it is still higher than the baseline precipitation by 2.01%. Precipitation keeps increasing by 5.11 and 8.05% at 3 and 4 °C warmer levels. Future ET_o is projected to increase by 3.39, 8.07, 11.65 and 15.23% and D is projected to increase by 6.76, 12.27, 17.56 and 22.70% at the four warmer levels, respectively. Aridity index is projected to decrease by 2.18% as temperature increase is 1 °C. Therefore, the moisture condition is likely to be more humid in China. However, I_a is projected to increase by 5.94, 6.22 and 6.55% at 2, 3 and 4 °C warmer levels, respectively. Therefore, the moisture condition is likely to be more arid in China, which is mostly attributed to the more significant increment in ET_o than P.

The regional difference in changes of climatic factors is shown in Figure 2. Future D and ET_o are likely to have similar changing trends in different ecoregions. The increasing trend of D is predicted over all ecoregions at different warmer levels, and it is most significant on the Tibetan Plateau. At 1 °C warmer level, ET_o is likely to increase in most ecoregions except the temperate humid/sub-humid region. At 2, 3 and 4 °C warmer levels, ET_o is likely to increase in all ecoregions,

and predominantly in the temperate humid/sub-humid ecoregion (Figure 2).

Future P and I_a are projected to change with great regional difference. At 1 °C warmer level, relative to the baseline period, P is likely to decrease in cold temperate humid region, tropical humid region and northwest arid region, while it increases in the other ecoregions. At 2 °C warmer level, P is likely to change from decreasing to increasing trend in cold temperate humid region and northwest arid region, and change from increasing to decreasing trend in temperate humid/sub-humid region and warm temperate humid/sub-humid region. At the warmer levels of 3 and 4 °C, P is likely to increase relative to previous warmer level. Future P is likely to increase most significantly in northwest arid region. As for I_a, at 1 °C warmer level, I_a is likely to decrease in temperate humid/sub-humid region, north semi-arid region, warm temperate humid/sub-humid region, sub-tropical humid region and the Tibetan Plateau region, while it increases in the other ecoregions. At 2 °C warmer level, I_a is likely to change from decreasing trend to the increasing trend in temperate humid/sub-humid region, north semi-arid region, warm temperate humid/sub-humid region and sub-tropical humid region, and change from increasing trend to the decreasing trend in northwest arid region. At 3 and 4 °C warmer levels, I_a is likely to increase in most regions except northwest arid region and the Tibetan Plateau (Figure 2).
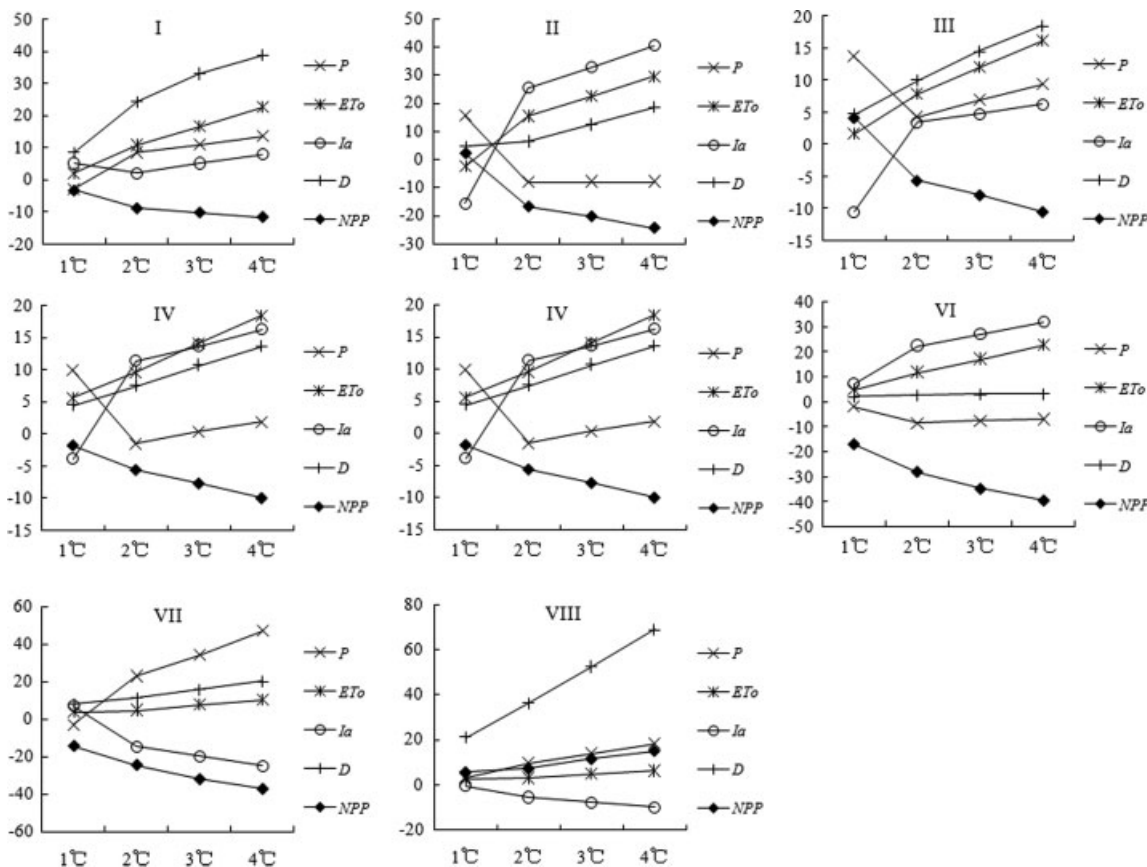

Figure 2. Changes in climatic factors and ecosystem NPP in different ecoregions in China (%).

3.2. Impact of future climate change on NPP at different warmer levels in China

3.2.1. Distribution of ecosystem NPP

At different warmer levels of 1, 2, 3 and 4 °C, the average terrestrial ecosystem NPP is projected to be 316.78, 289.66, 281.76 and 272.35 gC/m²/yr, respectively in China. Moreover, the geographical pattern of NPP is likely to be stable as the climate becomes warmer. NPP is relatively lower in Northwest China and higher in Southeast China, particularly higher in the Da and Xiao Hinggan Mountains and Changbai Mountains in Northeast China (Figure 3). NPP is projected to be the highest with 641.96 gC/m²/yr in cold temperate humid region, while the lowest with 79.73 gC/m²/yr in desert ecosystem in northwest arid region (Table II).

3.2.2. Impact of future climate change on ecosystem NPP

When projected temperature increase is around 1 °C relative to the baseline period, the average ecosystem NPP in China as a whole is likely to decrease by 2.67% due to climate change. However, the geographical pattern of projected impact indicates there are about 48% of the gridboxes showing decreases in NPP and 52% showing increases over China. Climate change would affect on ecosystems with significant regional difference over China. The average ecosystem NPP is likely to decrease in more than a half of the ecoregions. The most significant reduction is 17.26% in tropical humid region. Meanwhile, NPP in the Tibetan Plateau region, temperate humid/sub-humid region and north semi-arid region may increase by 5.72, 2.18 and 4.18%, respectively (Table II).

At 1 °C warmer level, according to the relationship between NPP changes and impact degree, as the absolute change in NPP is not expected to exceed 40%, the ecosystems are likely to be slightly impacted by future climate change in China and the eight ecoregions on average. Although large areas of ecosystems over China are expected to be slightly impacted, a minority of ecosystems are likely to be over moderately impacted which are mainly distributed in western China (Figure 4(a)). Around 7% of the ecosystems in China are likely to be exposed to over moderate adverse impact, and most of which is distributed in the northwest arid region. Exactly, in northwest arid region, almost 31% of the ecosystems are expected to be over moderately impacted, and 14% of the ecosystems are likely to be extremely impacted. On the contrary, about 4% of the total ecosystems in China are likely to be exposed to over moderate favorable impact, and almost all of which is distributed on the Tibetan Plateau. About 16% of the ecosystems are expected to be over moderately impacted, and 6% of the ecosystems are likely to be extremely impacted on the Tibetan Plateau.

As temperature increase is 2 °C relative to the baseline period, the average ecosystem NPP in China as a whole is likely to keep decreasing by 11.00%. But the geographical pattern of projected impact is different from

that of 1 °C warmer level. Gridboxes showing decreases in NPP are likely to be 70% over China. The ecosystem NPP is likely to decrease in most ecoregions. The most significant reduction is in tropical humid region by 28.17%. The two ecoregions with increasing NPP at 1 °C warmer level, i.e. temperate humid/sub-humid region and north semi-arid region, are likely to be influenced more obviously due to climate change. The ecosystem NPP in the two ecoregions is likely to change from increasing to decreasing trend. At the same time, only NPP on the Tibetan Plateau is likely to keep increasing by about 7.27%. The reduction of NPP in temperate humid/sub-humid region is similar to that in sub-tropical humid region (Table II).

At 2 °C warmer level, ecosystems are likely to be slightly impacted by future climate change in China and the eight ecoregions on average. Ecosystems to be slightly impacted are still expected to be predominant over China (Figure 4(a)). Compared with 1 °C warmer level, ecosystems to be adversely impacted slightly are likely to increase from 41 to 61% over China. However, areas of ecosystems impacted to a slight favorable degree are likely to decline from 48 to 23% over China. Ecosystems to be over moderately impacted are likely to be increased a little in almost the same distributing pattern. Ecosystems exposed to over moderate adverse impact are mainly distributed in the northwest arid region, occupying 38% of the total areas of this ecoregion. Meanwhile, ecosystems to be exposed to over moderate favorable impact are likely to be distributed in the Tibetan Plateau region occupying about 28% of the total area of this ecoregion.

As temperature increases are 3 and 4 °C relative to the baseline period, the average ecosystem NPP in China as a whole is likely to decrease by 13.43 and 16.32%, respectively. And the geographical pattern of the projected impact is very likely to be similar to that of 2 °C warmer level. The ecosystem NPP is likely to decrease in almost all ecoregions except for the Tibetan Plateau. The changing features of NPP are likely to keep the trends of 2 °C warmer with exacerbation to a certain degree. The most significant reductions are projected to be 34.89 and 39.50% in tropical humid region at 3 and 4 °C warmer levels, respectively (Table II).

At 3 and 4 °C warmer levels, the impact degrees of climate change on ecosystems in China and the eight ecoregions on average are expected to be the same with that of the 2 °C warmer level (Figure 4(c) and (d)). However, compared with 2 °C warmer level, the areas of ecosystems to be adversely impacted slightly are likely to decrease to 60 and 58% at 3 and 4 °C warmer levels, respectively over China. Areas of ecosystems impacted to a slight favorable degree are likely to decrease to 20 and 18%, respectively over China. Ecosystems to be exposed to over moderate adverse impact are likely to occupy 49 and 56% of the total area of the northwest arid ecoregion, respectively. Meanwhile, ecosystems to be exposed to over moderate favorable impact are likely
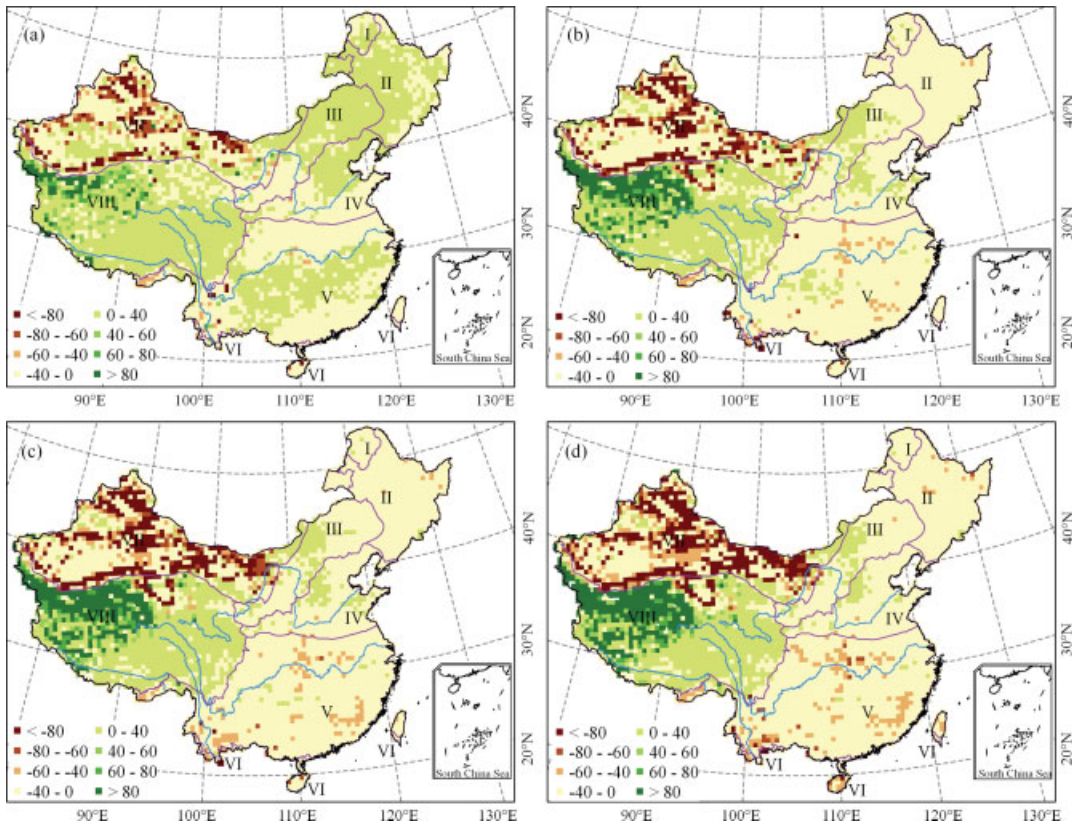
Figure 3. Spatial distribution of ecosystem NPP at four warmer levels in China (gC/m²/yr). (a) 1 °C warmer level, (b) 2 °C warmer level, (c) 3 °C warmer level and (d) 4 °C warmer level.
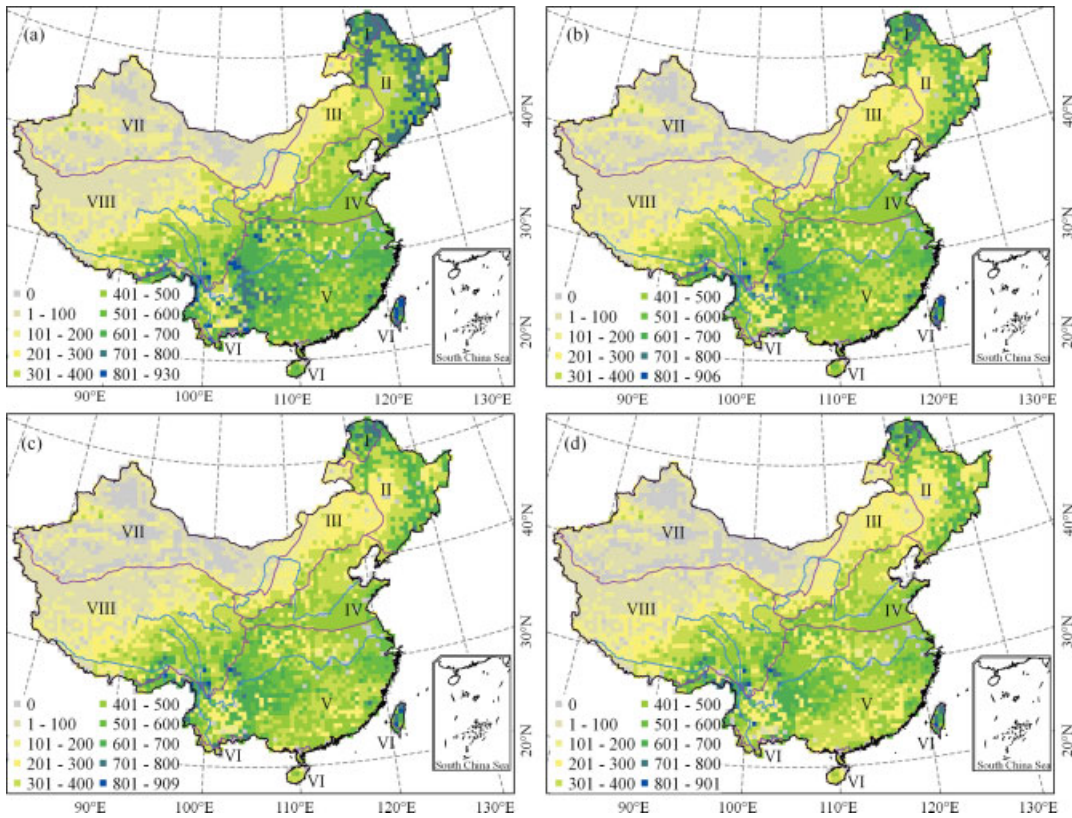

Figure 4. Spatial distribution of changes in ecosystem NPP at four warmer levels in China (%). (a) 1 °C warmer level, (b) 2 °C warmer level, (c) 3 °C warmer level and (d) 4 °C warmer level.

Table II. Change of average NPP in different ecoregions at four warmer levels in China.

Ecoregion	NPP (gC/m^2/yr)					Relative change (%)			
	Baseline	1 °C	2 °C	3 °C	4 °C	1 °C	2 °C	3 °C	4 °C
I	641.96	620.89	584.92	576.46	567.39	−3.28	−8.89	−10.20	−11.62
II	522.17	533.53	434.44	416.24	394.90	2.18	−16.80	−20.29	−24.37
III	254.74	265.38	240.44	234.72	228.06	4.18	−5.61	−7.86	−10.47
IV	410.56	403.30	387.88	379.35	370.05	−1.77	−5.52	−7.60	−9.87
V	549.49	512.07	461.83	439.85	413.40	−6.81	−15.95	−19.95	−24.77
VI	513.82	425.15	369.07	334.56	310.88	−17.26	−28.17	−34.89	−39.50
VII	79.73	68.35	60.36	54.42	50.32	−14.27	−24.29	−31.75	−36.89
VIII	200.38	211.85	214.95	223.45	230.55	5.72	7.27	11.51	15.05
China	325.46	316.78	289.66	281.76	272.35	−2.67	−11.00	−13.43	−16.32

to occupy 32 and 35% of the total area of the Tibetan Plateau ecoregion, respectively.

3.3. Relationship between future changes in NPP and climatic factors

The warming temperature and increasing precipitation are likely to benefit to vegetation growth, however, which are not certainty to induce increasing NPP, such as in cold temperate humid region, north semi-arid region, sub-tropical humid region and northwest arid region. Moisture condition plays an important role on changes in NPP. In most ecoregions over China, I_a is likely to increase and therefore moisture condition would become much more arid and induce decreases in NPP. On the contrary, I_a is projected to decrease and induce increases in NPP in the Tibetan Plateau region. However, the northwest arid region is an exception. Although I_a is projected to decrease, the ecosystem NPP is likely to decrease significantly on average at 2 °C or more warmer levels.

4. Conclusions and discussion

Under IPCC SRES B2 scenario, as projected temperature increases relative to the baseline period, the average ecosystem NPP in China as a whole is likely to decrease. According to the relationship between NPP changes and impact degree, as temperature increase is 1 °C, favorable or adverse impact on ecosystem would be almost equivalent with regional variation. At 2 °C warmer level, slight adverse impact would be significant. At 3 °C warmer level, moderate adverse impact would predominate. At 4 °C warmer level, moderate adverse impact regions would increase significantly. In general, the adverse impact degree of future climate change on natural ecosystems is likely to be more significant as temperature increases. But overall, the impact is always found to be a slight degree in China. Although it is hard to conclude whether 2 °C warmer is a dangerous level based on current research, it is a key level with essential changes indeed.

Ecosystems to be slightly impacted are expected to be predominant over China. Only a small part of ecosystems are expected to be over moderately impacted, particularly in the northwest arid region with adverse impact. The northwest arid region is expected to be the most vulnerable ecoregion, where desert ecosystems are likely to be severely damaged by climate change.

It is commonly reported that the future increase in CO_2 concentration will enhance NPP, whereas climate change alone could reduce global NPP. This was consistent with the future decreases in NPP over China in general. There is a problem in such 'off-line' simulations. The major changes predicted by the land surface model are unable to feedback from the atmospheric model. This as a potential issue needs to be improved in the future research.

References

Allen RG, Pereira LS, Raes D, Smith M. 1998. *Crop Evapo-transpiration-Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56*. United Nations Food and Agriculture Organization: Rome.

Anthony WK, Wilerred MP, Stan DW. 1997. The potential response of terrestrial carbon storage to changes in climate and atmospheric CO_2. *Climatic Change* **35**: 199–227.

Cao MK, Prince SD, Li KR, Tao B, Small J, Shao XM. 2003. Response of terrestrial carbon uptake to climate interannual variability in China. *Global Change Biology* **9**: 536–546.

Cao MK, Prince SD, Tao B, Small J, Li K. 2005. Regional pattern and interannual variations in global terrestrial carbon uptake in response to changes in climate and atmospheric CO_2. *Tellus B* **57**: 210–217.

Cao MK, Woodward FI. 1998. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biology* **4**: 185–198.

Fang JY, Piao SL, Field CB, Pan YD, Guo QH, Zhou LM, Peng CH, Tao S. 2003. Increasing net primary production in China from 1982 to 1999. *Frontiers in Ecology and the Environment* **1**: 293–297.

Gao Q, Yu M. 1998. A model of regional vegetation dynamics and its application to the study of Northeast China transect (NECT) responses to global change. *Global Biogeochemical Cycles* **12**: 329–344.

IPCC. 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, New York.

IPCC. 2007. Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, New York.

Ji JJ, Huang M, Liu Q. 2005. Modeling studies of response mechanism of steppe productivity to climate change in middle latitude semiarid regions in China. *Acta Meteorologica Sinica* **63**: 257–266 (in Chinese).

Ji JJ, Yu L. 1999. A simulation study of coupled feedback mechanism between physical and biogeochemical processes at the surface. *Scientia Atmospherica Sinica* **23**: 439–448 (in Chinese).

Jones R, Noguer M, Hassell D, Hudson D, Wilson S, Jenkins G, Mitchell J. 2004. *Generating high resolution climate change scenarios using PRECIS*. Met Office Hadley Centre, Exeter UK.

Ju WM, Chen JM, Harvey D, Wang S. 2007. Future carbon balance of China's forests under climate change and increasing CO_2. *Journal of Environmental Management* **85**: 538–562.

Lieth H, Whittaker RH. 1975. *Primary Productivity of the Biosphere*. Springer-Verlad Press: New York.

Lin ED, Xu YL, Wu SH, Ju H, Ma SM. 2007. China's National Assessment Report on climate change (II): climate change impacts and adaptation. *Advances in Climate Change Research* **3**: (Suppl.): 6–11.

Lv JH, Ji JJ. 2002. A simulation study of atmosphere-vegetation interaction over the Tibetan Plateau part II: net primary productivity and leaf area index. *Chinese Journal of Atmospheric Sciences* **26**: 255–262 (in Chinese).

Melillo JM, McGuire AD, Kicklighter DW, Moore B, Vorosmarty CJ, Schloss AL. 1993. Global climate change and terrestrial net primary production. *Nature* **363**: 234–240.

Met Office. 2002. The Hadley Center regional climate modeling system: PRECIS. http://www.metoffice.gov.uk/research/hadleycentre/pubs/brochures/B2002/precis.pdf.

Nakicenovic N, Alcamo J, Davis G, Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, Rovere ELL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, Rooijen S, Victor N, Zhou D. 2000. *Special Report on Emissions Scenarios of the Intergovernmental Panel for Climate Change*. Cambridge University Press: Cambridge, UK.

Nemani RR, Keeling CD, Hashimoto H, Jolly WM, Piper SC, Tucker CJ, Myneni RB, Running SW. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* **300**: 1560–1563.

Pan YD, Melillo JM, Kicklighter DW, Xiao X, McGuire AD. 2001. Modeling structural and functional responses of terrestrial ecosystems in China to changes in climate and atmospheric CO_2. *Acta Phytoecologica Sinica* **25**: 175–189.

Taskforce on China's National Assessment Report on Climate Change. 2007. *China's National Assessment Report on Climate Change*. Science Press: Beijing (in Chinese).

International Climate Change Taskforce. 2005. *Meeting the Climate Challenge-Recommendations of the International Climate Change Taskforce*. Institute for Public Policy Research: London.

UNFCCC. 1992. United Nations Framework Convention on Climate Change. New York. http://www.unfccc.int..

United Nations Development Programme (UNDP). 2007. *Human Development Report 2007-Fighting climate change: Human Solidarity in a Divided World.*. Palgrave Macmillan: New York.

White A, Cannell MGR, Friend AD. 1999. Climate change impacts on ecosystems and the terrestrial carbon sink: a new assessment. *Global Environmental Change* **9**: 21–30.

Woodward FI, Lomas MR. 2004. Vegetation dynamics: simulating responses to climatic change. *Biological Reviews* **79**: 643–670.

Wu SH, Zhao HX, Yin YH, Li SC, Shao XM, Tao B. 2006. Recognition of ecosystem response to climate change impact. *Advances in Climate Change Research* **2**: 59–66.

Xu YL, Jones R. 2004. Validating PRECIS with ECMWF reanalysis data over China. *Chinese Journal of Agrometeorology* **25**: 5–9 (in Chinese).

Xu YL. 2004. High resolution climatic scenarios in China based on RCM from the Hadley Center. *Climate Change Newsletter* **3**: 6–7 (in Chinese).

Zhang SH, Peng GB, Huang M. 2004. Derivation of earth surface parameters in vegetation properties supported by GIS techniques. *Climatic and Environmental Research* **9**(1): 80–91 (in Chinese).

Zhou GS, Zhang XS. 1996. Study on NPP of natural vegetation in China under global climate change. *Acta Phytoecologica Sinica*. **20**: 11–19 (in Chinese).