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Impacts of land use and climate change on regional net primary productivity

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Abstract: Combined with recent historical climate data and two periods of land use data sets from remote sensing data, we test the net primary productivity (NPP) data sets in North China modelled by the satellite data-driven Global Production Efficiency Model (GLO-PEM) for detecting the widespread spatial and temporal characteristics of the impacts of climate and land use change on the regional NPP. Our results show that over the past 20 years, the mean annual temperature in the study region has remarkably increased by more than 0.064 ℃, but over the same period, there has been a 1.49 mm decrease in annual precipitation and decrease in NPP by an annual rate of 6.9 TgC. The NPP changes in the study region were greatly affected by the average temperature and precipitation by ten-day periods as well as the seasonal temperature and precipitation in the study region. The correlation between seasonal NPP and seasonal precipitation and temperature is highly consistent with land cover spatially, and the correlation coefficient changes with the changes of vegetation types. The analysis reveals that the related areas in land use change only take up 5.45% of the whole studied region, so the climate changes dominate the impacts on the NPP in the whole study region (90% of the total). However, land use plays an absolute dominative role in areas with land cover changes, accounting for 97% of the total. From 1981 to 2000, the NPP in the whole study region remarkably reduced due to obvious precipitation decrease and temperature rise. Between two periods of land use (about 10 years), the changes in climate are predicted to promote a decrease in NPP by 78 ($\pm$0.6) TgC, and integrated impacts of climate changes and land use to promote a decrease in NPP by 87($\pm$0.8) TgC.
Key words: climate change; land use change; NPP; GLO-PEM; North China; Northeast China

1 Introduction

The global change caused by the continuous increasing concentration of atmospheric greenhouse gases has threatened the existence of human beings, and the importance of carbon dioxide emissions as a major environmental issue of international concern has grown substantially in the world (IPCC, 2000). At the same time, the Kyoto Protocol, the first and only realistic plan for achieving a worldwide reduction in greenhouse gas emissions, has been passed. Since there are many uncertain factors in the carbon sequestration estimation in ecosystems, many countries have objection to the protocol, which increases the world's interest in the carbon cycle of terrestrial ecosystem (Li *et al.*, 2003). Meanwhile, fully understanding the response of ecosystem to climate and land use changes is also necessary for human beings to protect the environment and for the need of enough food and energy because vegetation could act as carbon source or sink to greenhouse gas (B H Braswell *et al.*, 1997; David Schimel *et al.*, 2000). NPP is defined as the net flux of carbon from the atmosphere into green plants per unit time. Based on the study on the response of NPP to the environment (climate and land use changes), we can better understand the functions of ecosystem and its feedback to the changes of climate and social environment, and the study on ecosystem productivity is also the key to the sustainable utilization and development of agriculture and forestry (Cao *et al.*, 1998; Lobell *et al.*, 2002).

In the 20th century, the average annual temperature at earth surface rose by 0.06 ℃,

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especially over the last two decades (1979-1998), and the average temperature at the earth surface rose by 0.19 ℃ (Cao *et al.*, 2003). Peter T *et al.* found that with global climate accelerated warming, temperature was getting cold in the South Pole over the past 30 years, where ecosystem productivity showed obvious response with an annual decrease of 6%-9% (Peter T Doran, 2002). Tian Hanqin *et al.* applied the Terrestrial Ecosystem Model (TEM) to stimulate the response of the carbon stock in Amazon ecosystem to climate changes. In El Nino year when it was dry and warm, the ecosystem served as a carbon source, while in other warm and wet years, the Amazon forest ecosystem served as a carbon sink (Tian, 1998). Cao Mingkui *et al.*, based on IPCC IS92a scenario data, applied the CEVSA (Carbon Exchanges in the Vegetation-Soil-Atmosphere systems) model to stimulate the response of the ecosystem carbon cycle to the global climate changes during 1861-2070, and demonstrated that due to climate warming and CO_2 increase, the productivity of the global biome would remarkably increase. This trend would reduce with CO_2 saturation and weakened CO_2 fertilization (Cao *et al.*, 1998). At the same time, Cao Mingkui *et al.* used CEVSA model to stimulate and analyse the response of the terrestrial ecosystem carbon cycle to climate changes in the past 20 years in China, the result revealed that the temperature in Northeast China in the past 20 years has risen by 0.4 ℃, and the precipitation decreased by 4 mm, change in the net ecosystem productivity (NEP) in this area by 0.01 GtC (Cao *et al.*, 2003). Jorge L *et al.*, based on the data about future climate changes provided by IPCC, adopted the coupled climate-ocean model to stimulate and estimate the response of ocean carbon cycle to the climate warming induced by human activities (Jorge Lsarmiento *et al.*, 1998).

Over the last 20 years, great changes have taken place in climate and land cover in different regions of China. The climate was generally warming but each region differed greatly (Sha *et al.*, 2002). From the 1980s to the 1990s, the temperature in high-latitude areas in northern hemisphere has risen by 0.26 ℃, while 0.22 ℃ in low-latitude areas. However, in arid areas of northern China, the temperature has risen by 0.40 ℃, and in humid areas of southern China 0.34 ℃. The climate warming in the arid areas of northern China caused the average temperature in this area to be 1 ℃ higher than that in the 20th century (Cao *et al.*, 2003).

In recent years, Chinese scientists have studied the terrestrial net productivity in China with different models, while the study on the impacts of climate and land use changes on NPP was still in an initial stage (Piao *et al.*, 2001; Sun and Zhu, 1999; Chen *et al.*, 2001). This paper uses Global Production Efficiency Model (GlO-PEM) to calculate NPP data in China over the past two decades and analyze the characteristics of NPP spatial changes and their responses to climate and land use changes combined with the climate data and land use data in two periods of the studied region over the past 20 years (1980s to 1990s), which presented a basis for the study on the carbon stock and population carrying capacity in the region.

2 Methods

2.1 Study area

The study area is located in the northeastern part of China (between 101°50'W and 135°22'W, 30°N and 53°54'N) (Figure 1). As a semi-humid and semi-arid transect, the average precipitation over years in this region changed from 172 mm in east Inner Mongolia to 1037 mm in Liaodong and Shandong peninsulas. Located in the transition of China's warm temperate-temperate zone, the average annual temperature of the study region ranges from -11 ℃ in the northern part of Northeast China to 14 ℃ in Huaihe River basin. The elevation changes greatly, from 50 m in the North China and Sanjiang plains to 4586 m in Qinling and Taihang mountains. The land is mainly covered with croplands, forest and grassland respectively, taking up 39.2%, 26.94% and 26.17%, the unused land occupies 4.46% of the whole region, and the built-up land only 1.52% (Liu *et al.*, 2003a, b).

With vast territory, moderate temperature, sufficient precipitation, high soil productivity and dense population, this region is an economically-developed area, and also one of the main agricultural production bases in China. In recent years, the population growth, town expansion, and global climate warming have changed the population carrying capacity and structure of eco-environment of this region.

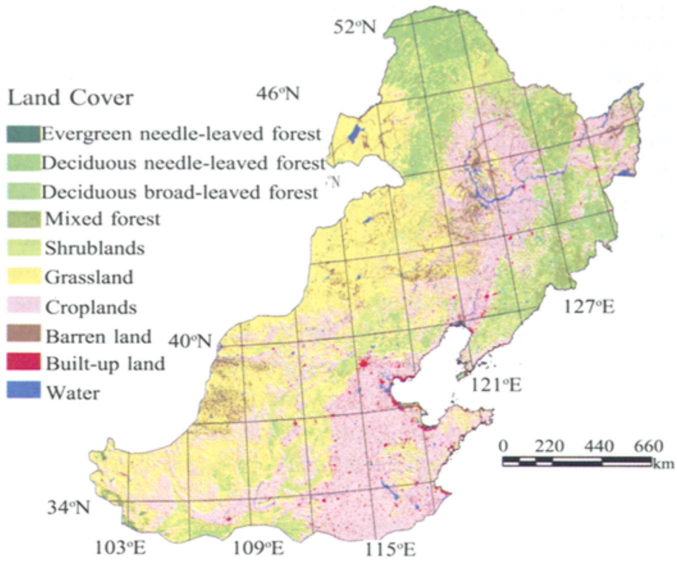

Figure 1 Study area and land cover classes in the 1990s

2.2 Models and data

In this study, we use the 20 years (1981-2000) of NPP data simulated by GLO-PEM and integrate weather data to analyze the impacts of climate and land use changes on NPP and its spatio-temporal characteristics.

2.2.1 Generation of NPP data based on GLO-PEM model Variations in NPP in the period were also calculated using GLO-PEM, a model driven entirely with remote sensing data. These data included both the normalized difference vegetation index (NDVI) and meteorological variables. GLO-PEM consists of linked components that describe processes of canopy radiation absorption, utilization, autotrophic respiration, and the regulation of these processes by environmental factors such as temperature, water vapor pressure deficit and soil moisture (Stephen D Prince *et al.*, 1995):

$$NPP = \sum_t [(S_t N_t)\varepsilon_g - R] \tag{1}$$

where S_t is the incident PAR in time t; N_t is the fraction of incident photosynthetically active radiation (PAR) absorbed by vegetation canopy calculated as a linear function of NDVI; and ε_g is the light utilization efficiency of the absorbed PAR by vegetation in terms of gross primary production. R is autotrophic respiration calculated as a function of standing above-ground biomass, air temperature, and photosynthetic rate. GLO-PEM was driven with the Pathfinder AVHRR Land (PAL) data at resolutions of 8 km and 10 days derived from channels 1, 2, 4 and 5 of AVHRR sensors aboard the NOAA-7, 9, 11, and 14 satellites (Cao *et al.*, 2003).

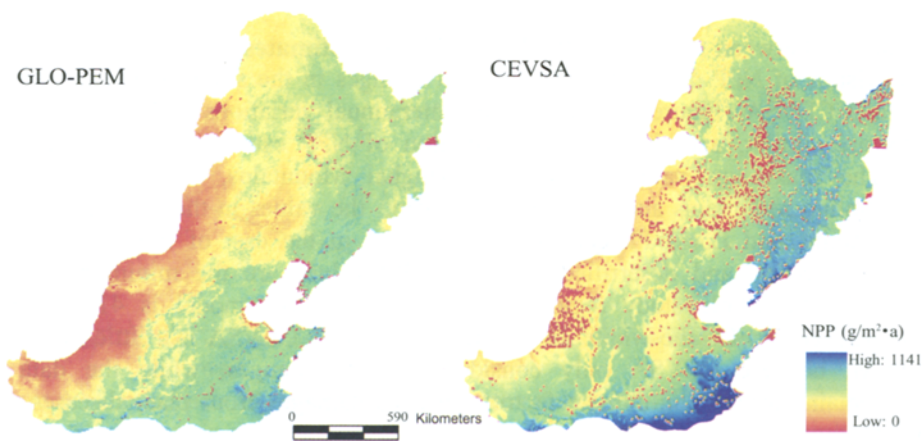

Figure 2 Average annual NPP in the study region estimated by GLO-PEM and CEVSA models 1981- 2000

2.2.2 Generation of NPP data based on CEVSA model The mechanistic model (CEVSA) was used to quantify the carbon exchanges between vegetation, soil and atmosphere based on physiological process and microorganism activities in soil. It estimates the variations and changes of the carbon stocks in vegetation and soil link photosynthesis, respiratory processes, allocation and accumulation of photosynthetic products, production of the litter, and transformation and decomposition of organic carbon in soil (Woodward F I *et al.*, 1995; F Ian Woodward, 1995).

The running of CEVSA model uses a meteorological database in ten-day period with a spatial resolution of 10 km. The meteorological data came from 671 meteorological stations of China Meteorological Administration, including precipitation, temperature, cloud, humidity and so on. First, we combine the daily meteorological data to an average value of each ten-day period, and then we, considering the impact of longitude, latitude and elevation, form a meteorological database of precipitation, temperature and cloud with a spatial resolution of 10 km with spline interpolation method. The soil texture data came from the second national soil survey conducted by the China Office of General Survey on Soil (1979-1994). The land use data came from China Remote-sensing Resource Environmental Database, the Chinese Academy of Sciences.

Based on Chinese temporal series data of 20 years stimulated by GLO-PEM and CEVSA, we use the boundary data of the study area to extract NPP time series data in the region for future study. The stimulation theory and data source of GLO-PEM and CEVSA models are independent each other. The former provides impactive reference of validation and verification for the result of GLO-PEM (Stephen D Prince *et al.*, 1995).

2.3 Data preparation and processing

The meteorological data in 20 years came from 671 meteorological stations of China Meteorological Administration, including daily precipitation, temperature, etc. First, we combine and arrange the daily meteorological parameters to that of ten-day period, and then we use binomial for internal interpolation under Arc/Info environment to calculate a ten-day meteorological database of precipitation and temperature with a resolution of 8 km. GLO-PEM simulation data came from the Department of Geography, University of Maryland. The data include Chinese NPP data from 1981 to 2000, time resolution of 10 days, and spatial resolution of 8 km. Based on the NPP data of the whole China, the data of each 10-day period in the 20 years is extracted and integrated consistently with the same projection and time-space resolution as meteorological data. This study applied these data to analyze the relationship between NPP and the changes in climate and land use.

3 Results

3.1 Comparison between the GLO–PEM and CEVSA estimates

The characteristics of NPP distribution and annual changes in the study region are estimated by GLO-PEM and CEVSA (Figures 2 and 3). The interannual variations in NPP estimated by the two models are similar, and the spatial distribution of NPP estimated by the two models is consistent. The maximum value occurs in Changbai Mountains, Liaodong and Shandong peninsulas, Qinling Mountains and Huaihe River basin, the values in the Northeast China Plain, Taihang Mountains and Loess Plateau are smaller, and in the east of Inner Mongolia mainly covered with grassland and desertified land the NPP values are the minimum. The average annual value in the whole study region estimated by CEVSA model is 412 gC/m^2 with a deviation of 138 gC/m^2. On the whole, the value estimated by CEVSA is a little higher than that by GLO-PEM, because CEVSA only considers climate changes, while the data used by GLO-PEM contain various non-climate factors, such as damages from plant diseases and insect pests, fire, etc.

3.2 Impacts of climate changes on NPP

Located in the humid, semi-humid and semi-arid transitional area of temperate zone, interannual precipitation in the study region changes greatly in annual precipitation. Over the past 20 years, the average precipitation was 522 mm with an interannual variation of 10.28% . In this region there was a significant decrease in annual precipitation by 1.49 mm. From 1981 to 1990, the average precipitation was 530 mm, while from 1991 to 2000, 514 mm (Figure 4). On spatial distribution, the annual precipitation in Xiao Hinggan Mountains, Changbai Mountains, Huaihe River basin and Qinling Mountains was about 1000 mm; that in Da Hinggan Mountains, Northeast China Plain, North China Plain was about 600 mm; and that in the east of Inner Mongolia Plateau and Loess Plateau, about 400 mm. The areas with annual precipitation less than 400 mm are semi-arid areas, accounting for 20% of the whole region; the areas with annual precipitation more than 800 mm are humid areas, only taking up 10%, and 70% of the areas are semi-humid areas (Figure 5 and Table 1). Precipitation in summer increased before 1998, but obviously decreased after 1998, with an annual variability of 12.7. After 1998, precipitation increased more obviously in autumn and winter, while remarkably decreased in spring. Precipitation varied greatly in spring and winter, at an annual rate of 25% and 38% respectively.

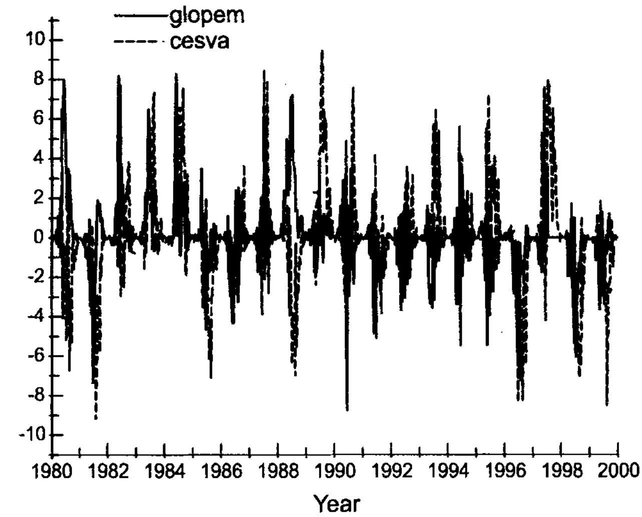

Figure 3 Average annual NPP relative changes in the study area estimated by GLO-PEM and CEVSA models (The NPP value in the figure is the difference between the actual value of each 10-day period and the average value of 20 years)

Great changes also took place in annual temperature. Over the past 20 years, the average annual temperature was 5.34 ℃ at an annual variability of 10.56%. The climate warming in this region was obvious, and the average temperature rose by 0.064 ℃ annually. From 1981 to 1990, the temperature rose by 0.5 ℃, and from 1991 to 2000), 0.32 ℃. The temperature gradually decreased from south to north, and the maximum temperature occurred in Qinling Mountains and Huaihe River basin, where the average annual temperature was up to 13 ℃; the average annual

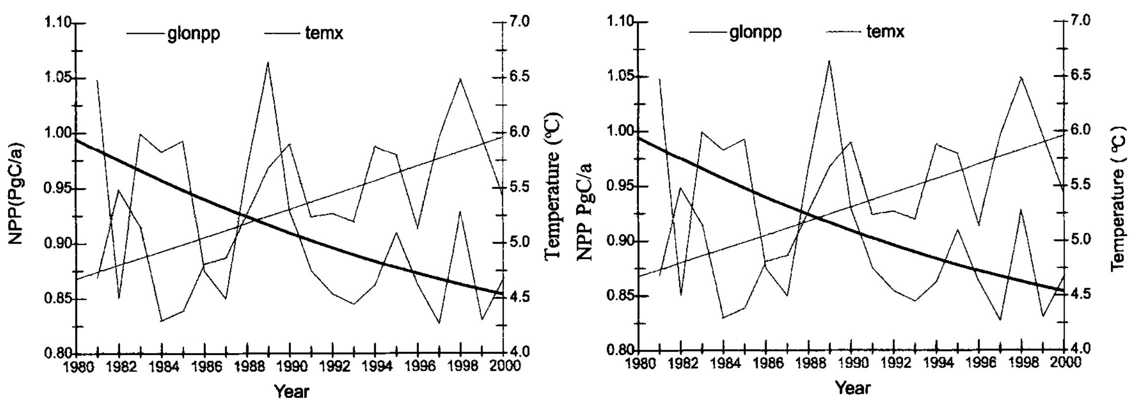

Figure 4 The impacts of temperature and precipitation on NPP (The index in the figure is the annual value in the whole studied region, i.e., each pixel area multiply the sum of indexes, and then divided by the sum of pixel areas. The smooth curve in the figure represents the fitted values of each factor to time change)

temperature in Shandong Peninsula, North China Plain and the southern part of the Loess Plateau was 10 ℃; and in Da Hinggan Mountains, Xiao Hinggan Mountains, and northeastern Inner Mongolia, below 0 ℃. Some 16% of the whole region has an average annual temperature higher than 10 ℃, 30% lower than 0 ℃ and 60% between 1 and 10 ℃. (Figure 5 and Table 1). Seen from seasonal changes, the temperature has generally risen in spring, summer and autumn annually by 0.048 ℃, 0.06 ℃ and 0.055 ℃ respectively, among which, the temperature rise in winter was most obvious with annual increase of 0.09 ℃.

Table 1 Average annual changes of NPP, temperature and precipitation in 5 years in Northeast and North China

Year	Temperature (°C)	Precipitation (mm)	NPP (PgC)
1981-1985	4.80	536.2	0.9742
1986-1990	5.30	525.7	0.9370
1991-1995	5.47	529.1	0.8692
1996-2000	5.79	499.6	0.8629

Annual NPP changes greatly in this region. The average NPP value in the past 20 years was 0.91 PgC (1 Pg = 10^{15}g) with an annual variability of 8.09% and annual decrease by 6.9 TgC (1 Tg = 10^{12} g). Over the past 20 years, NPP reduced obviously. The average NPP value in the former 10 years was 0.955 PgC, while in the latter 10 years 0.867 PgC, with a decrease of 88 Tg (Figure 6). Analyzed from seasons, over the past 20 years, the average NPP value in summer decreased obviously, annually by 4.73 TgC with an annual variability of 8.3%; in spring and autumn, NPP changed evenly. Although it reduced, the annual reduction rate was about 1 TgC. The NPP value in winter only accounted for 0.4% of the total annual NPP. Over the past 20 years, NPP generally decreased at an annual rate of 0.04 TgC, but the annual variability was up to 20%.

The annual changes of NPP show positive correlation with annual precipitation, and negative correlation with temperature. The correlation coefficient between NPP and precipitation is 0.3 at a significance level of 0.01, and that between NPP and temperature is -0.31 at a significance level of 0.01. Over the past 20 years, due to temperature rise and precipitation decrease, the NPP in the study region reduced obviously related to temperature and precipitation in the study region. Located in the semi-arid and semi-humid transect of north temperate

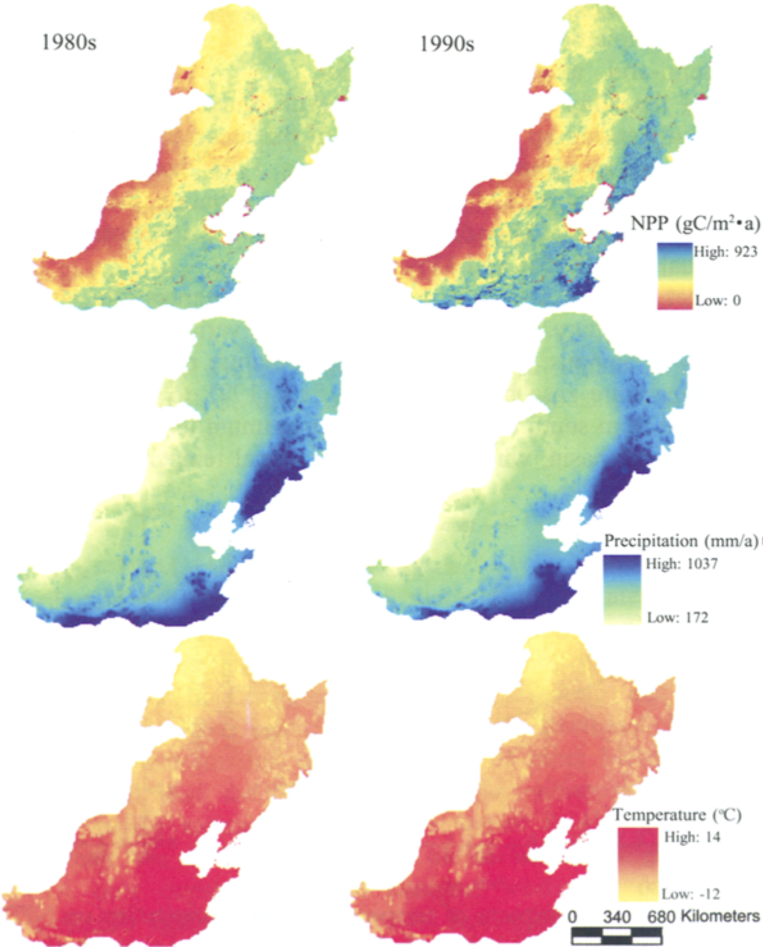

Figure 5 NPP, temperature and precipitation changes in Northeast and North China, 1981-2000

zone, vegetation growth is restricted by temperature and precipitation. Temperature and precipitation have an obvious impact on vegetation in the study region, so the growth of vegetation also has an impact on NPP values.

The changes of NPP in ten-day periods are mainly affected by precipitation and temperature. Over the past 20 years, the correlation coefficient between NPP and precipitation in ten-day periods was 0.407 ($p<0.01$), and that between NPP and temperature was 0.648 ($p<0.01$). The NPP changes within a year are closely related with precipitation and temperature. In the habitat of mesothermal zone, as long as there is enough precipitation, vegetation would have remarkable productivity under moderate temperature condition.

We collected the NPP, precipitation and temperature data covering the study region in four seasons to form seasonal data in 20 years, and generate the coefficients of the spatial correlations between NPP and precipitation and temperature by spatial correlation analysis. These data indicate that seasonal NPP has strong correlations with seasonal precipitation and temperature. The areas, where the correlation coefficient between NPP and precipitation is more than 0.56 and that between NPP and temperature is more than 0.7, account for 44% of the whole region, and the land cover of these areas is mainly forest; the areas, where the correlation coefficient between NPP and precipitation is 0.4-0.5 and that between NPP and temperature is 0.6-0.7, take up 23% of the whole region, and the land cover of these areas is mainly shrubland; the areas where the correlation coefficient between NPP and precipitation is 0-0.4 and that between NPP and temperature is 0-0.6, occupy 32% of the whole studied region, and the land covers of these areas are mainly grassland and cropland. From this we can see that seasonal NPP has strong relation with seasonal temperature and precipitation, which is not only related to the characteristics of the temperate zone in China that the precipitation and hot weather are in the same season, but more to the growth characteristics of different vegetations covering the land surface.

3.3 Impacts of land use changes on NPP

Based on the NPP data in 20 years estimated by GLO-PEM and the land use data in two periods (1980s and 1990s) obtained by remote-sensing macro-investigation, we study the impacts of land use changes on NPP. Although land use changes are continuous on space and time, we have to, in view of the limited land use data in the two periods, make the following scenario assumptions: during 1981-1990, the NPP data in 10 years simulated by GLO-PEM were mainly that of the land cover in the 1980s; similarly, the NPP data in 10 years during 1991-2000 were mainly that of the land cover in the 1990s; thus, the anomaly of the average annual NPP data during 1991-2000 and 1981-1990 (climate impact was excluded) might be treated as the impacts of land use changes on the NPP in the study region. The climate impacts in these two periods could be represented by the difference of NPP data in two consecutive years in this period.

The land use change areas only account for 5.45% of the whole study region (Figure 7 and Table 2). Where no land use change happens, the cropland covers 38.59%, forestland 27.63%, grassland 26.53%, water area 1.58%, urban land 1.26%, and unused land 4.4%. Where land use changes, the land use changes as follows: the cropland increases from 25.56% of the whole area in the 1980s to 50.85% in the 1990s; the forestland decreases from 26.18% in the 1980s to 14.61% in the 1990s; the grassland decreases from 31.76% in the 1980s to 18.99% in the 1990s, the water area decreases from 4.74% in the 1980s to 3.98% in the 1990s, the built-up land increases from 0.69% in the 1980s to 6.25% in the 1990s; the unused land decreases from 11.07% in the 1980s to 5.32% in the 1990s.

From the above we can find that the characteristics of the land use changes in this region are: the agricultural land and the built-up land increased remarkably, while other land use types generally decrease. The change tendency is that the unused land and water area are converted into grassland or plough land, the grassland and forestland are converted into croplands or built-up land, and the cropland is occupied by construction land. Such characteristics of land use succession has the impact on NPP as follows: the cultivation of the unused land and water area

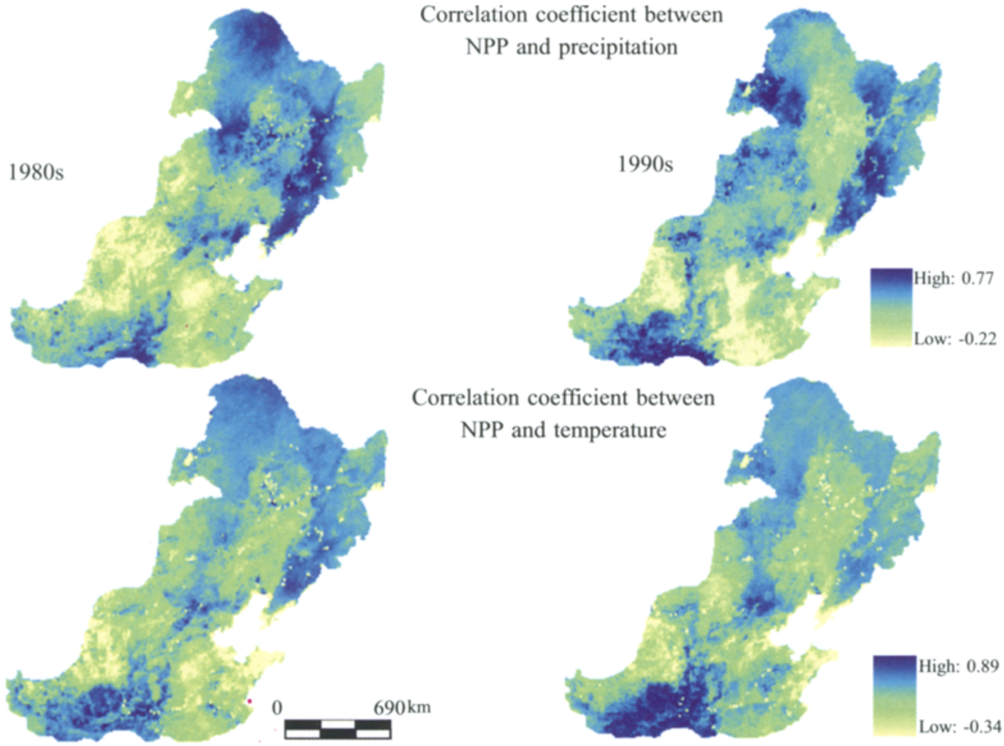

Figure 6 Correlation coefficient between NPP and temperature and precipitation in the 1980s and the 1990s (The correlation coefficient in the figure was calculated with average values in each 10-day period in 10 years)

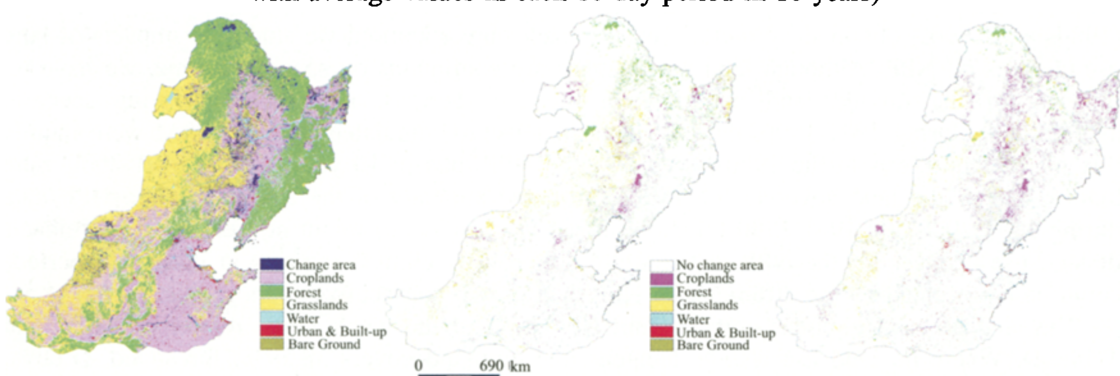

Figure 7 Land use changes (left: the land cover in the areas where no land use changes; middle: the land cover in the 1980s in the areas where land use changes; right: the land cover in the 1990s in the areas where land use changes)

into grassland or cropland may cause NPP to increase, the conversion of grassland and forest land into cropland or land for construction may cause NPP to reduce, and the occupation of cropland as the built-up land may cause NPP to decrease sharply. If the anomaly of NPP data in the area where land use changes in two consecutive years is adopted to represent the impact of climate changes and the difference changes within the range from -0.2 TgC to 0.2 TgC, in the whole area where land use changes, the NPP reduces 9.13 TgC due to climate and land use changes, but the climate impact only takes up around 26% of the overall impact.

In this region, the increased cropland turned from grassland, forestland and unused land is 33,000 km^2, resulting an increase of NPP in the areas by 10.89 TgC. The forestland decreases by

Table 2 Land use changes in the study region (in 10,000 km^2)

Land type	No change	Change (1980s)	Change (1990s)	Change areas
Croplands	92.6	3.34	6.65	3.31
Forestlands	66.3	3.42	1.91	-1.51
Grasslands	63.7	4.15	2.48	-1.67
Water	3.8	0.62	0.52	-1.00
Built-up area	3.0	0.09	0.82	0.73
Unused land	10.6	1.45	0.69	-0.75
Total	240.0	13.07	13.07	

15,000 km^2, of NPP to reduce by 7.48 TgC. The grassland decreases by 16,700 km^2, causing a reduce of NPP by 6.91 TgC. 1000 km^2 of water area are turned into cropland and grassland, NPP to increase by 0.49 TgC. The land for construction increases by 7300 km^2, causing NPP to reduce by 3.1 TgC. The unused land decreases by 7500 km^2, causing NPP to reduce by 3.03 TgC. Thus, in the whole area where land use changes, the NPP reduction resulted from land use changes is about 9($\pm$0.2) TgC over the past 10 years (the interval between two land use period), excluding climate impact (about $\pm$0.2 TgC annually). In the areas where no land use changes, the climate impact causes NPP to reduce by around 78 TgC. In the whole studied region, the NPP reduces by about 87 TgC due to climate and land use, and the impact of climate changes accounts for about 90%, while that of land use changes about 10%. The total decrease of NPP takes up about 9% of the total average annual NPP in this region (910 TgC).

As to the whole study region, the climate has a dominative impact on NPP (90% of the total impact). As to the areas where land use changes, land use plays a dominant role, which accounts for 97% of the total impact. Seen from the total NPP value in many years in the whole region, the NPP change caused by climate and land use changes only occupies 9% of the total average annual value.

4 Discussion and conclusions

This paper, using the NPP data of North China in 20 years estimated by GLO-PEM model driven by remote sensing data combined with climate data, together with the land use data in two periods, analyzes the spatiotemporal characteristics of the impacts of climate and land use changes on NPP from 1981 to 2000.

The results show that over the past 20 years, the average temperature of the study region remarkably increased by 0.064 ℃ annually, while precipitation obviously decreased by 1.49 mm annually. Generally speaking, the NPP reduced annually by 6.9 TgC. The NPP changes were greatly affected by the average temperature and precipitation in ten-day periods as well as the seasonal temperature and precipitation in the study region. Seasonal NPP is closely related to seasonal temperature and precipitation. The correlation between seasonal NPP and seasonal precipitation and temperature is highly consistent with vegetation cover spatially, and the correlation coefficient changes with the types of vegetation cover, indicating that the seasonal climate changes and different vegetation covers have an interactive impact on the NPP in the study region.

Over the past 20 years, the temperature of the whole study region has obviously risen and precipitation decreased, causing the NPP to reduce remarkably. Between two land use periods (about 10 years), NPP reduced by 78 ($\pm$0.6) TgC. Since the areas where land use changes only take up 5.45% of the whole study region, the climate has a dominative impact on the NPP (90% of the total). As to the areas where land use changes, land use plays a dominant role, 97% of the total impact, causing the NPP to reduce by 9 ($\pm$0.2) TgC (Fang J *et al.*, 2002) over the past 10 years.

Seen from the total value of average annual NPP in many years in the whole region, the NPP fluctuation due to climate and land use changes only occupies about 9% of the total value. The impact of land use changes on NPP only takes up less than 1% of the total value of the average annual NPP in many years in the whole region. Due to the interaction of climate and land use, the NPP in this region reduces by 87 (±0.8) TgC.

Since it is very difficult to obtain the data of continuous large-area land use and quantify the human-induced impacts on ecosystem (John P Caspersen *et al.*, 2000; Guo and Gifford, 2002), plus the complexity and hysteresis of the impacts of land use changes on ecosystem (Vleeshouwers *et al.*, 2002; Peter M Cox *et al.*, 2000), there exists uncertainty in the study results.

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