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Research Article

Modelling the Responses of Carbon Fluxes to Climate Change in Northeast China Forests using IBIS

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Abstract: Assessing the long-term exchange of carbon dioxide between terrestrial and the atmosphere is an important priority of the current climate change research. In this regard, it is particularly significant to provide valid data on fluxes of carbon over representative ecosystems. In this study, we used a modified process-based terrestrial ecosystem model (Integrated Biosphere Simulator, IBIS), which represents biogeochemical and biophysical process, coupling the carbon, nitrogen and water cycles on each specific time steps, to generalize our understanding of the temporal and spatial variability of Net Primary Productivity (NPP), Net Ecosystem Productivity (NEP) and Soil Respiration (RS) over northeast China to climate change for the period 1961 to 2080. The model results demonstrate a powerful approach to integrate and expand our knowledge of climate changes on northeast China forest carbon dynamics now and in the future.

Keywords: Climate change, integrated biosphere simulator, net ecosystem productivity, net primary productivity, northeast China, soil respiration

INTRODUCTION

Forests play an important role in the terrestrial carbon cycle. The processes of photosynthesis, respiration and litter decomposition in terrestrial plant communities consume and/or produce large amounts of carbon dioxide, the predominant greenhouse gas in global warming. Hence monitoring and modelling the dynamics of carbon mass fluxes in forest ecosystems is a crucial activity in studies of global climate change.

The temperate forest in the northeastern China is the largest piece of temperate mixed forests, accounting for more than one-third of forested area and standing tree volume in the whole nation. They make a large contribution to global carbon storage and carbon budget, thus the climate change.

In the last decade, a number of studies have been carried out at the national scale for estimating China's net primary productivity (NPP) and C budget, possible responses to past climate change; inter annual climate variability and future climate change. For example, based on forest inventory data, Fang *et al*. (2001) found substantial increases in C storage of China's forests during the 1980s and 1990s due to national afforestation and reforestation programs. Using a biogeochemical model, Piao *et al*. (2005) concluded that vegetation productivity in China has increases significantly due to climate change and rising atmospheric CO_2 and the largest increases in net primary productivity were observed in broad leaf and needle leaf mixed forests in northeast China. Although several such large scale C budget projects have been carried out in China, few studies of them have attempted to estimate temporal variations and trends in the terrestrial C budget in northeast China in response to climate variability. Furthermore, no efforts have been made to analyze the spatiotemporal patterns of C balance in northeast China's forests at centennial scale. To predict more accurately the response of the forest ecosystem carbon balance and reduce the uncertainty in estimating forest carbon budgets under a changing climate, we must improve our ability to understand the complex positive and negative feedbacks between climate and processes in forest ecosystems.

Carbon budget of forest ecosystems cannot be directly and fully measured at the regional scale, so the model method has been an important means which can not be replaced in the research on the terrestrial carbon cycle. In this study, a process-based model of the terrestrial carbon cycle (IBIS) was used to investigate long-term effects of climate change from 1961 to 2080 on NPP, Net Ecosystem Productivity (NEP), Soil Respiration (RS). The specific objectives of this study were:

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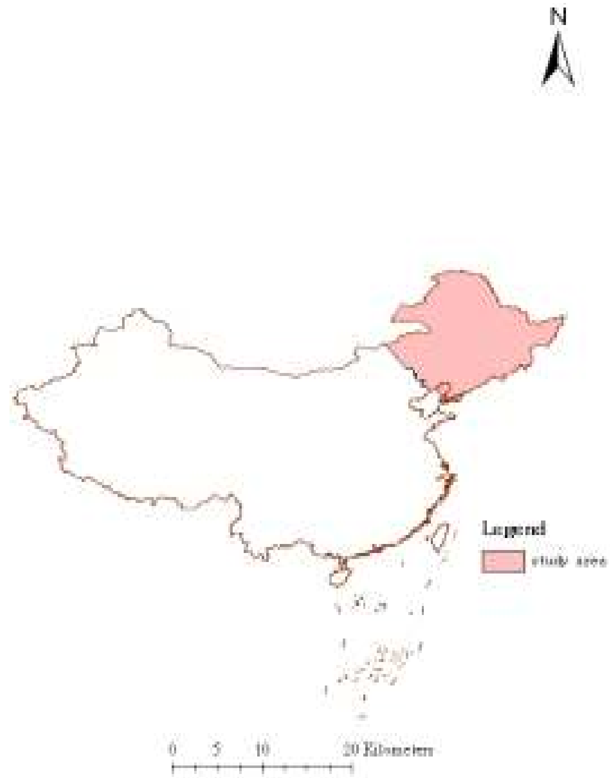

Fig. 1: Study area

To generalize our understanding of the temporal and spatial variability of NEP, NPP and RS at 1 km resolution using IBIS model that was developed and validated for northeastern China forests.

- To calculated the carbon balance for northeastern China forests during 1961 to 2080 and to demonstrate how ecosystems response to meteorological anomalies and to investigate uncertainties of historical variation in vegetation NPP NEP and RS driven by climate change.

STUDY SITE

The study was carried out in forested lands of northeast China (Fig. 1) located in the southern edge on Eurasia boreal forests and consists of Heilong Jiang, Ji Lin and Liao Ning provinces and the eastern part of inner Mongolia Autonomous Region. The study region, within the approximate latitudinal range of 38.6-53.6°N and longitudinal range of 114.8-145°E , contains 5 major forest types including boreal deciduous needle leaf forest, temperate evergreen needle leaf forest, temperate deciduous broad leaf forest, temperate needle-broad leaf forest, mixed forest. Major soil type is dark brown soil. Climates of forest in this study area are characterized by warm summer, cold winter, abundant precipitation and short growing season and are controlled by high latitude East Asia monsoon, changing from warm temperature, temperature to cool temperate zone from south to north and from humid, semi-humid to semiarid zone from east to west. For whole study area, the annual average temperature ranges from -9.9-11.2°C and precipitation ranges from 464-2243 mm. The forests in northeast China represent a transition zone between boreal and temperate vegetation, which is believed to be sensitive to changes in climate and play an important role in the carbon cycle in East Asia. In this study, we did not consider the agriculture region located in the central part of northeast China.

MODEL MODIFICATION AND VALIDATION

The complete model description and modification are presented in Liu *et al*. (2011). For applying a model of carbon cycle over northeast China we have to validate it at point scale. A model calibration was demonstrated earlier with the collection of NPP and RS data selected from Maoer Shan database and the model was applied to simulating NPP and soil surface CO_2 in temperate forests in northeast China. We show that the processed model is suitable for projecting inter annual changes of NPP and RS at the point scale.

INPUT DATA

The IBIS requires three datasets: climate, soil and vegetation data. The historical climate data including monthly mean temperature, precipitation, relative humidity and daily mean wind velocity averaged over 1961-1990 generated from National Weather Forecast Station were used as model input to spin up model simulation about 3000 years so that soil carbon pools can arrive at an equilibrium state. Mean daily temperature range, cloud coverage and precipitation days were interpolated to 1 km resolution based on the previous climate data recorded in northeast China. The interpolated anomalies were applied to IBIS to produce time series of future climates from 2020 to 2080 for each pixel. The daily weather conditions for 1961-2080 will be generated by Richardson weather generator based on the meteorological data series from these above datasets.

Site-specific parameters and initial conditions, such as soil texture (clay, silt and sandy content), bulk density, soil water content at field capacity, saturated hydraulic conductivity of the soil, were obtained from Kucharik *et al*. (2000). Some site-specific parameters were unavailable, requiring modification of existing values for temperate and boreal forests-a parameterization procedure took Peng *et al*. (1998) as reference. These parameters include: maximum gross and net forest production, optimum and maximum temperature for production, scaling factor for potential evapotranspiration and carbon storage in leaf, root and wood.

A vegetation map of China in 2006 was used to parameterize the model for each pixel. This map was produced from a nation wide land-use map at a 1 km resolution interpreted from MODIS imagines. The land cover map was classified into 5 forest types, including deciduous Needle leaf Forest (DNF), evergreen Needle leaf Forest (ENF), deciduous Broad leaf Forest (DBF), mixed forest: ENF and DBF (MF) and shrubs. The representation species of DNF, ENF, DBF and MF were temperate Larix forest, aspen-birch forest, pinus koreinsis forest, oak forest and Leaf Area Index (LAI) for the current climate were originated from MODIS with resolution of 1 km×1 km in 2006. We aggregated these vegetation types and LAI as our model input.

RESULTS AND DISCUSSION

The spatial and temporal dynamics of temperature and precipitation strongly influence a wide range of biotic and abiotic process in temperate forests, including plant gross and net primary production, decomposition and mineralization and site energy and carbon balance. However, relatively few spatial and temporal temperature and precipitation modeling have been made in these forest ecosystems.

According to IPCC AR4 climate scenario, the northeast China climate shows variability and a significant positive trend in temperature and precipitation during the period 1961-2080 (except in 2020) (Fig. 2). Climatic conditions during 2020-2080, will warmer and drier than the first 30-year (1961-1990) normal (2 °C and 909 mm) at whole study area. On the average, mean temperature in northeast China's forested areas increases by 6 °C during 1961-2080 (from +2 to +^{8} °C), whereas precipitation increases by only about 9% (from 909 to 988 mm). The changes in

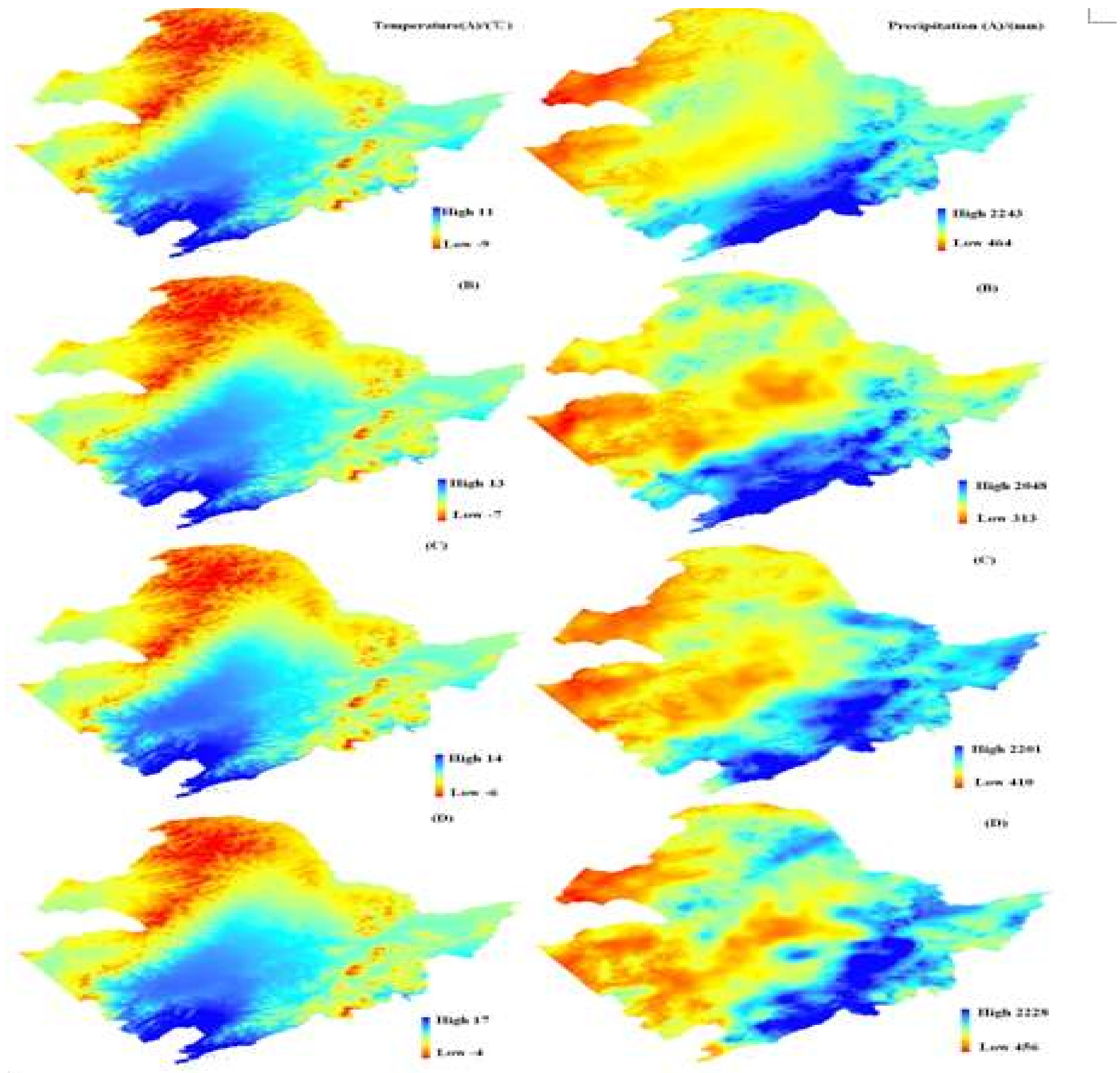

Fig. 2: Temporal and spatial patterns of temperature and precipitation in northeast China for years of 1961-1990 (A), 2020 (B), 2050 (C) and 2080 (D)

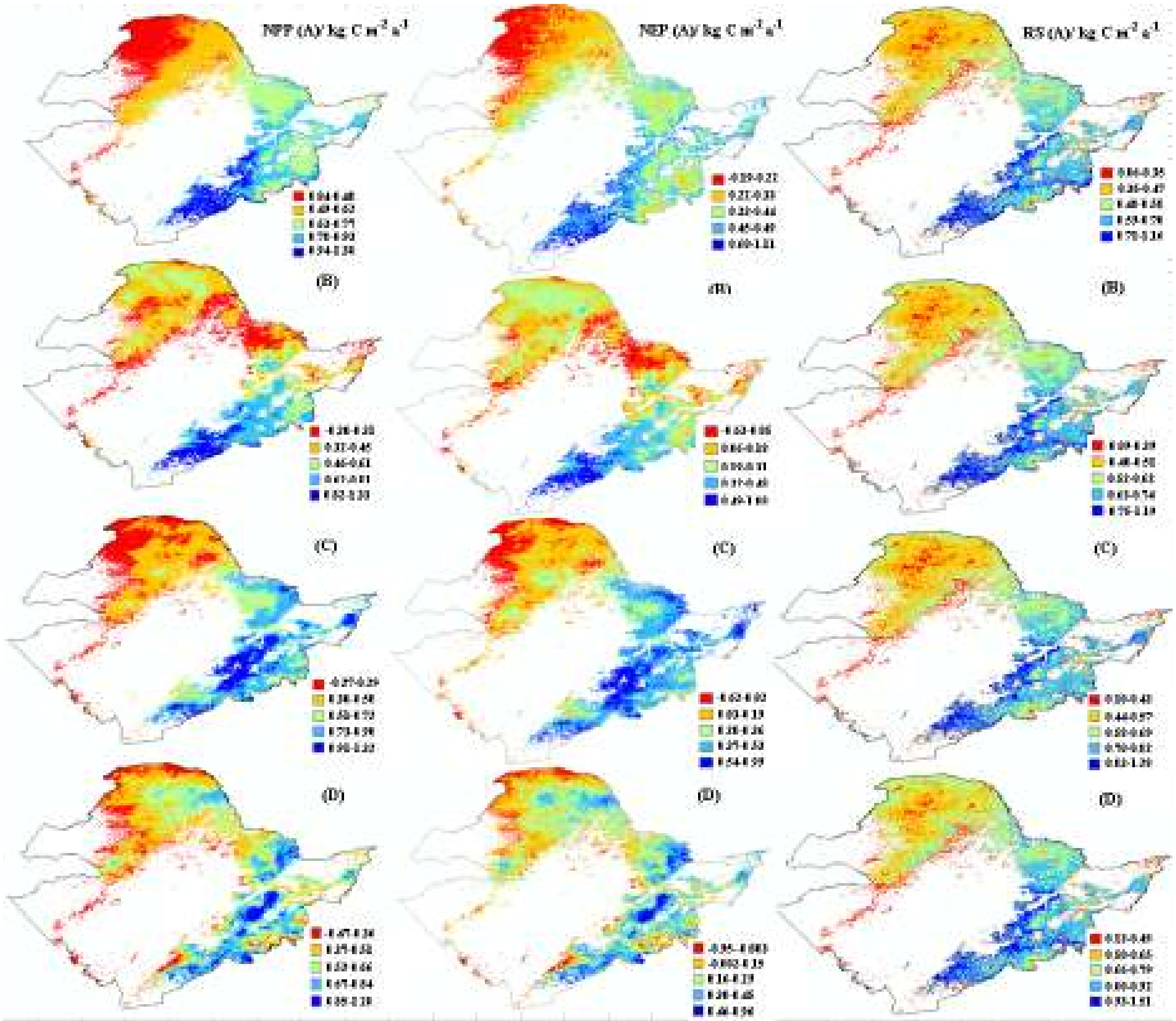

Fig. 3: Spatial and temporal patterns of NPP, NEP and RS for years of 1961-1990(A), 2020 (B), 2050 (C) and 2080(D) by IBIS simulated

temperature and precipitation are not spatial uniform (Fig. 2). Increases in temperature occur in all forest areas, especially in Daxing'anling and Xiaoxing'anling and mainly occurs during two distinct periods: between 1961-1990 and 2020. While increases in precipitation mainly occur in Xiaoxing'anling and Wanda Shan, except in 2020 precipitation decreased 13% compared to 1961-1990.

Figure 3 illustrates the distribution of average NPP, NEP, RS derived by IBIS during the period of 1961 to 2080, indicating strong spatial gradients which reflect gradients in temperature and precipitation conditions. All results show similar spatial patterns: NPP, NEP and RS clearly decreased from southeastern to northwestern areas. Because of the warm-humid climate, the highest NPP, NEP and RS all appear in the southeastern part of northeast China. In the northwestern part, the high latitude (>52°N) and limited temperature cause short GDD and less radiation, as a result, NPP, NEP and RS in this part of northeast China are very low, mostly lower than 0.36, 0.22, 0.13 kg C m^2/yr, respectively. The largest NPP, NEP and RS are simulated not more than 1.4, 1.1, 1.5 kg C m^2/yr^-, respectively. The regional area-average NPP, NEP and RS were simulated to be 0.51-0.66, 0.22-0.35 kg, 0.53-0.74 kg Cm^2/yr, respectively for the period 1961-2080. The average NPP seems reasonable in comparison with typical values in this area: e.g., 0.48- 0.68 kg C m^2/yr for Chinese temperate forests by Jiang *et al*. (1999) and 0.634 kg C m/yr for Asia by Matsushita and Tamura (2002) , NEP was a little higher than the other research, e.g., Ito 2008.

During the simulated period, variability in the weather conditions caused inters annual variability in the carbon budget. Historical (1961-1990) NPP was predicted to be in the range 0.04-1.38 kg C m/yr (Fig. 3). After 1990s, NPP did not increase consistently until 2020s. It is possibly due to the effect of temperature and precipitation acting together. Over the period 2020-2080, NPP increased by 0.07 kg C m^2/yr or

13.8% in IBIS simulation. The quick increase in NPP of China's forests is during the 2050s and 2080s or about 1.8 °C temperature increase, at which point it begins to level off. For NEP, IBIS suggest that most regions of northeast China have accumulated C, except in north Mongolia in which IBIS simulation indicates a substantial C loss. Total NEP in northeastern China steadily decreased by 0.13 kg C m^2/yr from 1961-1990 to 2080, mainly due to increased RS ranging from 0.53-0.74 kg C m^2/yr caused by warmer temperature and higher precipitation. Decreases in NEP appear after about 2.3 °C of warming since 2020. Thus, seems reasonable in comparison with Lemans, who cited a 1999 study by Cramer *et al*. (2001) suggested that carbon sink decreased occurs somewhere between 2 and 3 °C temperature increases. Similarly, Cramer *et al*. (2001) indicated that the terrestrial carbon sink begins level off by 2050 and decreases by the end of the century.

As a process-based model, the IBIS well represents key ecosystem processes such as photosynthesis, respiration, decomposition and nutrient and water cycling. The modified IBIS produced reasonable simulations of temporal and spatial variations of NPP, NEP and RS under the climate change at regional scale in the future, improved our understanding of future carbon dynamic in the forest in northeast China. However, there are still uncertainties on the simulations, which may be attributed to ecosystem characteristics and model limitations. First, model is specifically concerned with the interacting dynamics of C and nitrogen in the ecosystem and, as a consequence, may be difficult to parameterize at a larger scale. Second, IBIS used unified parameters, such as CO_2 and O_2 concentration, which did not explicitly predict the effects of change in climate. Elevated CO_2 may favor NPP and increase water use efficiency of trees. However, trees may adapt to change CO_2 concentrations and the effect may diminish soon (De-Vires and Posch, 2011). Another factor influencing C sequestration and linked to climate change is the rise in temperature and changes in water availability. Higher temperature accelerates enzymatic processes and therefore biomass accumulation, unless other factors are limiting. At very high temperatures enzymatic activity will be hampered, leading to growth reductions. Increasing temperature may also increase annual NPP by lengthening the growing season.

Third, model did not consider topography variations, which may effect the land radiation and water cycle and thus carbon cycle precision. Finally, model estimates come from the assumption of a steady state and the omission of age-related changes in forest carbon balance. An improved understanding of carbon dynamics of various forest ecosystems by considering stand age is needed for regional and national carbon balance assessments, since forest age is a critical factor deterring forest ecosystem carbon fluxes. Many components of the forest carbon cycle are related to forest age, including stand water use, soil carbon, live biomass increment and litter decomposition (Bradford *et al*., 2008). Due to the high variation in stand age, efforts directly or indirectly (remote sense based) to estimate ecosystem carbon flux for large areas must take into account forest age structure among forest types.

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