

Simulating Net Carbon Budget of Forest Ecosystems and Its Response to Climate Change in Northeastern China Using Improved FORCCHN

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Abstract: As dominant biomes, forests play an important and indispensable role in adjusting the global carbon balance under climate change. Therefore, there are scientific and political implications in investigating the carbon budget of forest ecosystems and its response to climate change. Here we synthesized the most recent research progresses on the carbon cycle in terrestrial ecosystems, and applied an individual-based forest ecosystem carbon budget model for China (FORCCHN) to simulate the dynamics of the carbon fluxes of forest ecosystems in the northeastern China. The FORCCHN model was further improved and applied through adding variables and modules of precipitation (rainfall and snowfall) interception by tree crown, understory plants and litter. The results showed that the optimized FORCCHN model had a good performance in simulating the carbon budget of forest ecosystems in the northeastern China. From 1981 to 2002, the forests played a positive role in absorbing carbon dioxide. However, the capability of forest carbon sequestration had been gradually declining during the the same period. As for the average spatial distribution of net carbon budget, a majority of the regions were carbon sinks. Several scattered areas in the Heilongjiang Province and the Liaoning Province were identified as carbon sources. The net carbon budget was apparently more sensitive to an increase of air temperature than change of precipitation.

Keywords: net carbon budget; climate change; northeastern China; improved FORCCHN

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1 Introduction

The carbon cycle in terrestrial ecosystems has been one of the critical scientific issues in studying global climate change and it is also a focus component of large scale multidisciplinary international programs in global climate change that have developed since the 1980s. Evaluation of the carbon cycle is important for predicting the future climate, since an acceleration of a climate warming is expected due to carbon cycle feedbacks (Cox *et al.*, 2000).

Terrestrial ecosystems and the climate system are

closely coupled, particularly through the cycling of carbon among vegetation, soils, and the atmosphere (Cao and Woodward, 1998a). The ecosystem's carbon fluxes are controlled by the processes of photosynthesis, plant (autotrophic) respiration, and soil (heterotrophic) respiration. The difference between plant photosynthesis and respiration is defined as the net primary productivity (NPP), while the difference between NPP and soil respiration is defined as the net ecosystem productivity (NEP) to represent net carbon flux from the atmosphere to the ecosystems (Cao and Woodward, 1998b), i.e., the net carbon budget. Among many factors affecting these

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processes, the most obvious ones at the global scale are elevated CO₂ concentration and climatic change, which directly or indirectly influence the carbon fluxes by interactively controlling ecological and physiological processes (Houghton and Woodwell, 1989; Amthor, 1995). Fire and deforestation are also important influencing factors. It is suggested that changes of climate and atmospheric carbon dioxide concentration have modified the carbon cycle and consequently render terrestrial ecosystems as substantial carbon sinks (Houghton and Woodwell, 1989; Amthor, 1995; Keeling *et al.*, 1996).

Relative to other ecosystems, forest ecosystems play a leading role in the global carbon cycle regulation because of their enormous carbon stocks, sequestration capacity, and productivity (Watson *et al.*, 2000; Wang *et al.*, 2008). Small shifts in the balance between photosynthesis and ecosystem respiration can result in a great difference in the net uptake or emission of carbon dioxide (CO₂) by forests (Pregitzer and Euskirchen, 2004; Wang *et al.*, 2007). In China, forests are mainly composed of young to middle-aged secondary forests and plantations (Huang, 2008), and therefore, the ecosystem's carbon cycle is far from being stabilized. Hence, quantification of forest carbon sources and sinks is an important part of national inventories of net greenhouse gas emissions in a country (Phillips *et al.*, 2000; Wang *et al.*, 2007).

The forest ecosystems in the northeastern China play an important role in the national carbon budget because they comprise more than 30% of the total forest area (Fang and Chen, 2001) and 40% of the total forest biomass of China (Wang *et al.*, 2008), including the southern boundary boreal forests of Eurasia in the Da Hinggan Mountains of the Heilongjiang Province and Inner Mongolia, which are especially sensitive to projected climate change (Zhou, 1997). In the past decade, a number of studies have been carried out at the national scale for estimating the net primary productivity and its responses to future climate change in China. For example, Wu (1997) suggested that Northeast China would benefit from the rise of the CO₂ level in the atmosphere and climate warming, with a 10%–15% increase of NPP over the most parts of the region. Fang *et al.* (2003) and Piao *et al.* (2005) also pointed out that China's terrestrial NPP had been significantly increased due to the increases in temperature, precipitation, and CO₂ concen-

tration, and the largest increase in NPP was observed in broad-leaf and needle-leaf mixed forests in the northeastern China. Wang *et al.* (2008) investigated the spatio-temporal changes of the forest's NPP in China over the recent two decades based on a geographically weighted regression (GWR) with a cumulative remote sensing index, and found out that the average forest NPP increased by about 0.72% from the 1980s to late 1990s. Other relevant studies focused on forest biomass (Fang *et al.*, 2001; Li *et al.*, 2004; Pan *et al.*, 2004), forest carbon storage (Fang *et al.*, 2001; Piao *et al.*, 2001; Zhu, 2005), possible responses to past climate change (Peng and Apps, 1997; Arrota and Boer, 2005), and net carbon dioxide losses (Piao *et al.*, 2007). These previous studies are important for understanding various aspects of forest dynamics, NPP, and carbon balance; however, very limited studies have been conducted to investigate the carbon budget of forest ecosystems in the northeastern China at a regional scale so far.

It is very difficult to get a clear picture of the net carbon budget of ecosystems at the regional or global scales through direct measurements. Therefore, ecological models have practically become one of the best approaches that integrate all available data sets for large-scale applications for investigating the terrestrial carbon cycle. Generally speaking, models of terrestrial carbon cycles mainly include biogeographic models such as ecophysiological-based biome model (BIOME) (Prentice, 1993) and mapped atmosphere-plant-soil system (MAPSS) (Neilson *et al.*, 1992), biogeochemical models such as grassland and agroeco-system dynamics model (CENTURY) (Parton, 1993), biome model-biogeochemical cycle model (BIOME-BGC) (White *et al.*, 1997) and terrestrial ecosystem model (TEM) (Melillo *et al.*, 1993), dynamic global vegetation model such as lund-potsdam-jena guess (LPJ-GUESS) (Hicker *et al.*, 2003), and so on. The disadvantages of the biogeographic and biogeochemical models are that they ignore the correlations and interactions between structure and function of ecosystems. As an alternative, forest ecosystem process-based models are increasingly used to better understand how the key processes that govern the dynamics of the forest ecosystems interact. Process-based models play a key role in predicting how the carbon cycle of forest ecosystems will be affected by climate change (Verbeeck *et al.*, 2006). Recently, analogous models such as individual-based model of

vegetation dynamics HYBRID3.0 (Friend *et al.*, 1997), individual-based forest ecosystem carbon flux model (INTCARB) (Song and Woodcock, 2003), LPJ-GUESS (Hicker *et al.*, 2003), FORCCHN (Yan and Zhao, 2007) have been used in investigating the forest carbon cycle.

This study is designed to investigate the carbon budget of forest ecosystems and its response to climate change in the northeastern China by taking advantage of the improved FORCCHN model to simulate the dynamic mechanism of carbon budget of young forests. The objective of this research is to test the improved FORCCHN model and apply it for providing scientific evidence for reasonably estimating carbon sequestration and the dynamics of forest ecosystems in the region under various future climate change scenarios.

2 Materials and Methods

2.1 Study area

This study is conducted in the forest areas of the northeastern China, located in the southern edge of the Eurasia boreal forests, including Heilongjiang, Jilin, and Liaoning provinces, and the eastern part of Inner Mongolia Autonomous Region (Fig. 1). The study area (38° – 54° N, 110° – 136° E) covers about 1 240 000 km² (about 12.9% of the total country's area). There are four dominant forest types, including temperate evergreen coniferous forests (*Picea* spp., *Pinus* spp.), deciduous coniferous forests (*Larix gmelinii*), deciduous broadleaf forests (*Robinia pseudoacacia*), and mixed forests (*Pinus koraiensis*) (Zhou, 1997). Major soil types include dark-brown soil, brown coniferous forest soil, calcic chernozems and meadow soil. The climate in the

study area is characterized by warm summer, cold winter, abundant precipitation, and short growing season, largely controlled by the East Asian monsoon, changing from a warm temperate zone to a cool temperate zone from south to north, and from a humid zone to a semi-arid zone from east to west. For the whole study area, the average annual temperature ranges from -4°C to 11.5°C and the annual precipitation ranges from 250 mm in the west to 1100 mm in the east (Tan *et al.*, 2007). The forests in the northeastern China represent a transition zone between boreal and temperate vegetation, and therefore is likely to be sensitive to the changes in climate and play an important role in the carbon cycle in East Asia (Wang *et al.*, 2002; Houghton, 2003). The study area was selected not only because of the availability of forest inventory data, forest sampling plots, and soil data needed for running the FORCCHN model, but also because this area represents a pronounced climatic gradient through the boreal forests in Baikal Mountain to the mixed forests in the Changbai Mountains and is an ideal region for exploring the relationship between forests and climates and carbon dynamics under climate change.

2.2 FORCCHN model

The carbon budget model FORCCHN (Yan and Zhao, 2007) is established based on individual tree species. The major processes considered in the model and the flow charts are illustrated in Fig. 2. The FORCCHN model includes five submodels: 1) Initialization module: It randomly selects the numbers of trees, tree types, and tree sizes according to the leaf area index, the proportions of evergreen trees and deciduous trees, and tree

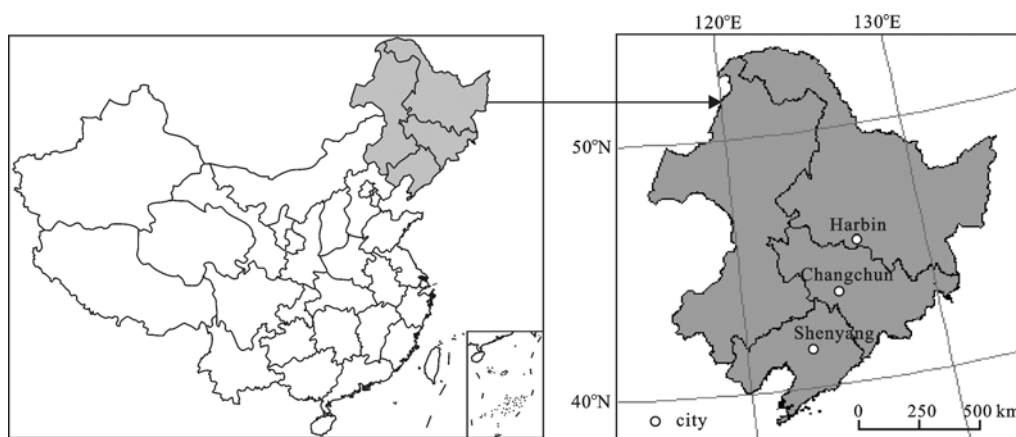


Fig. 1 Location of study area

types, maximizing close to the actual forest. 2) Ecoclimatic module: It mainly calculates the daily water budget and energy budget. 3) Carbon balance module: The step is day-to-day. It calculates daily changes in the carbon amount of photosynthesis, respiration, and the litter of each tree, and then obtains the carbon budget of forest ecosystem. 4) Soil carbon and nitrogen budget module: The step is also run at daily basis. It calculates daily changes in the carbon amount of respiration, transfer, and nitrogen mineralization of the litter layer and the soil humus layer, and then obtains the carbon budget and available nitrogen in the soil of the forest ecosystem. 5) Annual tree growth and carbon balance module: The step is year-to-year. It calculates the fruits litter and the carbon for structure growth according to the cumulative carbon budget calculated by the daily carbon budget, and then computes the annual increased carbon according to the diameter of the breast and height of the trees.

The carbon budget equations of individual tree and forest stands are calculated as follows (Yan and Zhao, 2007):

$$\frac{dx_i}{dt} = GPP_i - t_resp \times (RM_i + RG_i) - L_i \quad (1)$$

$$\frac{d(\sum x_i)}{dt} = \sum GPP_i - t_resp \times (\sum RM_i + \sum RG_i) - \sum L_i \quad (2)$$

where $\frac{dx_i}{dt}$ denotes the daily carbon budget increment of the i th individual tree ($i = 1, 2, \dots, n$) ($t = 0, 1, 2, \dots$,

n) (kgC/d); $\frac{d(\sum x_i)}{dt}$, the daily carbon budget increment of a forest stand (kgC/d); GPP_i , the daily gross primary productivity of the i th individual tree (kgC/d); RM_i , the daily maintenance respiration of the i th individual tree (kgC/d); RG_i , the daily growth respiration of the i th individual tree (kgC/d); L_i , the daily litter amount of the i th individual tree (kgC/d), and t_resp , the effect of air temperature on plant respiration that ranges from 0 to 1.

The spatial resolution of the FORCCHN is 10 km × 10 km, and the simulations and a variety of environmental factors are assumed to be uniform in every grid. The model input is simply designed to include three parts, namely daily meteorological data, soil characteristics data, and vegetation characteristics data. The meteorological data are provided by the China Meteorological Administration, including daily maximal, minimum and average air temperature, precipitation, relative humidity, wind and total radiation. The soil characteristic data are from 1 : 1 4 000 000 soil texture maps generated by the Institute of Soil of Science, Chinese Academy of Sciences, including soil field capacity, buck density, carbon pool, nitrogen pool, soil water content, sand content, silt content and clay content. While the vegetation characteristic data are derived from National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite images, including maximal leaf area index, minimum leaf area index and forest cover ratio. The model parameters consist of tree ecological type parameters and soil parameters. The tree species are cate-

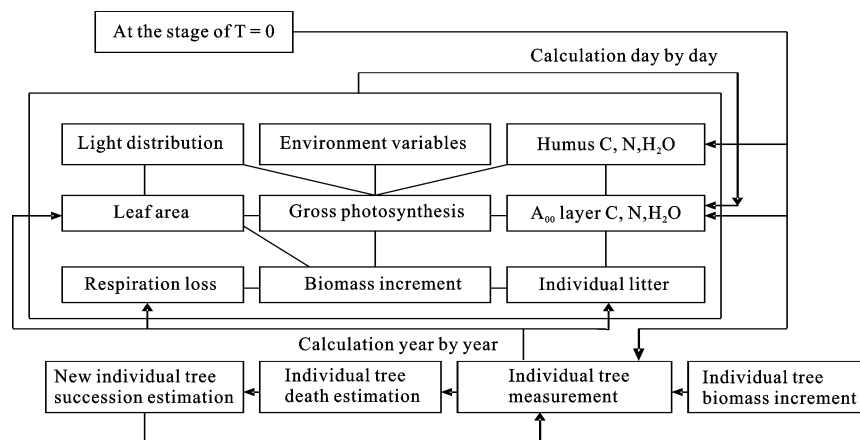


Fig. 2 Primary processes and flow charts of FORCCHN model

gorized into four ecological types according to their habitats and generic characteristics (evergreen broad-leaved tree, deciduous broad-leaved tree, evergreen conifer tree, deciduous conifer tree), such as shade tolerance (climax) species and sun tolerance (pioneer) species in Northeast China. The soil parameters include soil organic matter parameters, litter pool decomposition parameters, and soil physical parameters. Especially, the soil physical parameters are mainly dependent on the geographical location.

The detailed descriptions of the FORCCHN model's features, structure, mathematical representation, basic parameters, building strategy and validation were previously provided by Yan and Zhao (2007). This current study presents our first attempt to test the improved FORCCHN model and apply it for studying the carbon budget of the forest ecosystems and its response to climate change in the northeastern China.

2.3 Improved FORCCHN model

Forest's hydrological effect is an important function of forest ecosystem. With dense forest canopy foliage, there are twice distribution processes of the atmospheric precipitation mainly through the canopy interception. However, in the original model, it does not consider the forest canopy interception. Here, we add canopy interception mechanism to the original model. The FORCCHN model has been further improved and applied through adding variables and modules of precipitation (rainfall and snowfall) interception by tree crown, understory plants and litter. Especially rainfall interception is described by a variable experience model.

When rainfall (R) is less than maximal critical rainfall (R^*), the relationship between rainfall interception and rainfall is linear.

$$R_{\text{int}} = \alpha \times R \quad (3)$$

where R_{int} is rainfall interception (mm); α is the ratio between rainfall interception in the canopy and total rainfall (%); R is rainfall (mm).

When rainfall is greater than or equal to maximal critical rainfall, rainfall interception is expressed as:

$$R_{\text{int}} = \beta \times LAI \times R^* \quad (4)$$

where β is plant functional type parameter, changing from 0.02 to 0.06 for different vegetation basing on the results from Gerten *et al.* (2004); LAI is leaf area index.

Snowfall is an important input for soil water in the

northeastern China. We take into account two kinds of intercepted snow, namely potential intercepted snow and sublimed intercepted snow. The formulas are given as:

$$S_{\text{pi}} = \varepsilon \times S \quad (5)$$

where S_{pi} is potential intercepted snow (mm); S is snow (mm); ε is the ratio between snowfall interception in the canopy and total snowfall (%).

$$S_{\text{si}} = Ra / J \quad (6)$$

where S_{si} is sublimed intercepted snow (mm); Ra is daily average radiation (W/m^2); J is 2845.0 MJ/m^3 , standing for sublimation latent heat of snow.

In addition, we suppose that the interceptions by understory plants and litter are 9% of total rainfall according to the report from Cai *et al.* (1996).

2.4 Climate change analysis and scenario selection

In order to assess the impact of climate change on the carbon budget of forest ecosystems, it is necessary to get a clear picture of climate change. Here we applied approaches for a small-scale scenario study (Lu, 2006). We analyzed meteorological data from 1980 to 2002 in the study area, and found that the average annual temperature showed an elevated trend ($R^2 = 0.41$, $p < 0.01$), but the average annual precipitation mainly presented fluctuations instead of any significant trends (Fig. 3).

According to most recent projections from the IPCC Fourth Assessment Report (Bates *et al.*, 2008), the global average temperature is expected to increase $1.1\text{--}6.4^\circ\text{C}$ from 1990 to 2100, and the precipitation will also likely increase in the high latitudes; under some scenarios, the precipitation will change (increase or decrease) 20% by 2100. Temperature and precipitation are two basic factors simulated in the climate change scenarios. Consequently, based on our preliminary results, we assume the conditions of a temperature increase and a precipitation increase or decrease in our simulation (Table 1).

3 Model Validation

3.1 Comparing simulated vegetation carbon densities with other research results

In this study, we analyzed and compared the average carbon densities of forest ecosystems (Table 2) in the northeastern China simulated by the improved FORCCHN with other estimations. From Table 2, we could

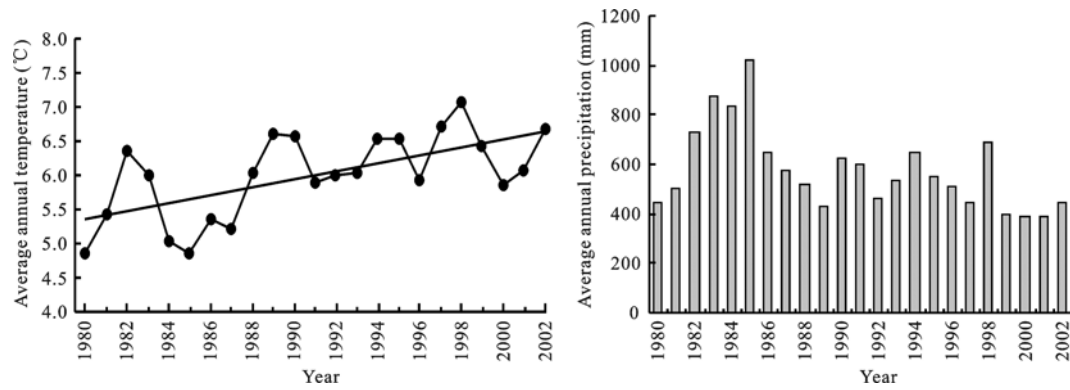


Fig. 3 Changes of average annual temperature and precipitation from 1980 to 2002 in northeastern China

Table 1 Climate scenarios in FORCCHN model

Code	Climate scenario
T0P0	Current climate condition
T3P0	Daily temperature increased by 3°C and precipitation unchanged
T0P2	Daily average temperature unchanged and precipitation increased by 20%
T0P-2	Daily average temperature unchanged and precipitation decreased by 20%
T3P2	Daily average temperature increased by 3°C and precipitation increased by 20%

Notes: T, air temperature; P, precipitation

know that the simulated average carbon densities showed a better consistency with other estimations, and could be used in the following analysis.

3.2 Comparing simulated NPP with observed NPP

In this paper, we used the observed NPP data of forest survey obtained by the Chinese Ministry of Forestry from 1989 to 1993 (Luo, 1996) to compare with simulated NPP. The results showed that the simulated NPP

by improved FORCCHN was more close to the observed NPP in the northeastern China, indicating that the optimized FORCCHN model had a good performance compared with the original model through adding variables and modules of precipitation (rainfall and snowfall) interception by tree crown, understory plants and litter (Fig. 4).

4 Results

4.1 Spatio-temporal dynamics of net carbon budget of forest ecosystems

The net carbon budget of forest ecosystems in the northeastern China was simulated by using the improved FORCCHN. From 1981 to 2002, the total amount of the net carbon budget showed a significant trend of an interannual decrease, with a fluctuation between 0.012 PgC/yr to 0.023 PgC/yr (Table 3). The forest ecosystems in the region were carbon sinks, and

Table 2 Comparisons of simulated average carbon density by improved FORCCHN with other researches

	Study period	Average carbon density (kgC/m ²)				
		Deciduous broad-leaved forest	Evergreen coniferous forest	Deciduous coniferous forest	Coniferous and broad-leaved mixed forest	Forest ecosystem
This study	1981–2002	6.22	9.76	15.18	5.26	6.32
Tao (2003)	1981–2000	6.71	8.45	12.2	5.57	7.24
Fang <i>et al.</i> (1998)	1989–1993	6.86–9.45	5.8–8.5	10.3–15.7	9.7–14.7	–
Huang (2008)	1961–1990	7.01	7.98	10.09	4.95	–
Zhou <i>et al.</i> (2000)	1989–1993	4.78	2.95–7.56	4.33–6.02	6.47	–
Wu (2002)	1989–1993	5.58	3.93	–	5.58	–
Liu (2001)	Early 1990s	2.83	3.6	3.13	3.94	3.47
Luo (1996)	1989–1993	–	–	–	–	5.71
Wang (1999)	1989–1993	–	–	–	–	5–15

Note: –, no data

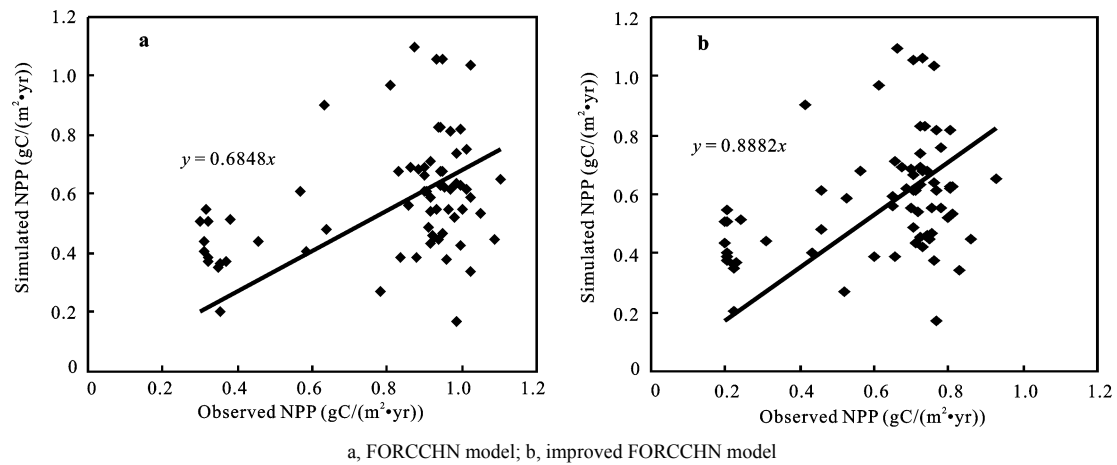


Fig. 4 Comparing simulated net primary productivity (NPP) with observed NPP

every year they absorbed 0.017 PgC on average from 1981 to 2002. It indicated, therefore, that forest ecosystems in the northeastern China played an active role in reducing the concentration of greenhouse gases in the atmosphere and delaying climatic warming from 1981 to 2002.

Average spatial patterns of the net carbon budget from 1981 to 2002 were summarized in Fig. 5. As far as the average spatial distribution was concerned, a majority of the regions was carbon sinks. In the northeast of Inner Mongolia and part regions of the Heilongjiang Province, sequestered carbon was less than 300 gC/(m²·yr). Meanwhile, in most of the region, the absorbed carbons fluctuated between 300 gC/(m²·yr) to 700 gC/(m²·yr), with the greatest carbon sink of more than 800 gC/(m²·yr) in several densely forested areas of

the Liaoning Province in the south. Several scattered areas in the Heilongjiang Province and the Liaoning Province were identified as carbon sources. The maximal released carbon was mostly found in the north and middle sections of Heilongjiang Province.

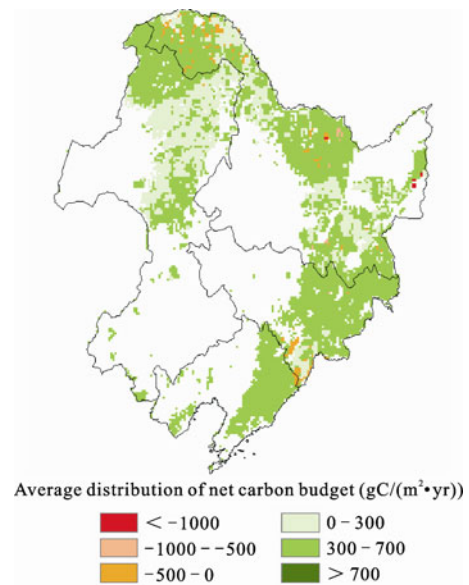


Fig. 5 Average distribution of net carbon budgets of forest ecosystems from 1981 to 2002 in northeastern China

Table 3 Average net carbon budgets projected by improved FORCCHN model under current climate change scenario in northeastern China

Year	Net carbon budget (PgC)	Year	Net carbon budget (PgC)
1981	0.020	1992	0.018
1982	0.019	1993	0.016
1983	0.016	1994	0.015
1984	0.021	1995	0.018
1985	0.019	1996	0.018
1986	0.021	1997	0.015
1987	0.018	1998	0.016
1988	0.02	1999	0.013
1989	0.023	2000	0.012
1990	0.018	2001	0.012
1991	0.018	2002	0.015

4.2 Response of net carbon budget to climate change

The impacts of climate change on the net carbon budget of forest ecosystems in the northeastern China were simulated. The projected total net carbon budget showed a strong fluctuation and significant trend of an interannual decrease under different climate scenarios (Table 4).

Table 4 Net carbon budgets projected by improved FORCCHN model under different climate change scenarios in northeastern China (PgC)

Year	Different climate change scenarios				Year	Different climate change scenarios			
	T3P0	T3P2	T0P2	T0P-2		T3P0	T3P2	T0P2	T0P-2
1981	0.023	0.024	0.021	0.022	1992	0.025	0.025	0.018	0.021
1982	0.023	0.023	0.02	0.023	1993	0.02	0.021	0.017	0.017
1983	0.02	0.022	0.018	0.016	1994	0.02	0.02	0.015	0.015
1984	0.023	0.024	0.022	0.019	1995	0.022	0.022	0.018	0.02
1985	0.024	0.024	0.02	0.019	1996	0.021	0.021	0.018	0.018
1986	0.025	0.025	0.021	0.022	1997	0.019	0.019	0.015	0.017
1987	0.022	0.022	0.018	0.02	1998	0.019	0.02	0.016	0.015
1988	0.024	0.024	0.02	0.021	1999	0.017	0.017	0.013	0.014
1989	0.028	0.028	0.023	0.025	2000	0.015	0.015	0.012	0.014
1990	0.023	0.023	0.018	0.022	2001	0.015	0.015	0.011	0.013
1991	0.022	0.022	0.018	0.018	2002	0.017	0.017	0.015	0.016

Notes: T3P0, daily temperature increased by 3°C and precipitation unchanged; T3P2, daily average temperature increased by 3°C and precipitation increased by 20%; T0P2, daily average temperature unchanged and precipitation increased by 20%; T0P-2, daily average temperature unchanged and precipitation decreased by 20%

On the basis of the same precipitation, the average net carbon budget under the scenario of a 3°C increase in temperature (T3P0) increased by 21.90% compared with that of no change in temperature (T0P0). However, on the basis of the same 3°C increase in temperature, the average net carbon budget under the scenario of a 20% increase in precipitation (T3P2) increased by 1.43% compared with that of no change in precipitation (T3P0), and on the basis of the same no change in temperature, the average net carbon budgets under the scenarios of a 20% increase in precipitation (T0P2) and a 20% decrease in precipitation (T0P-2) increased by 1.16% and 7.01%, respectively, than that of no change in precipitation (T0P0) (Table 4). It might indicate that the net carbon budgets of forest ecosystems in the northeastern China were more sensitive to an increase of air temperature than a change of precipitation.

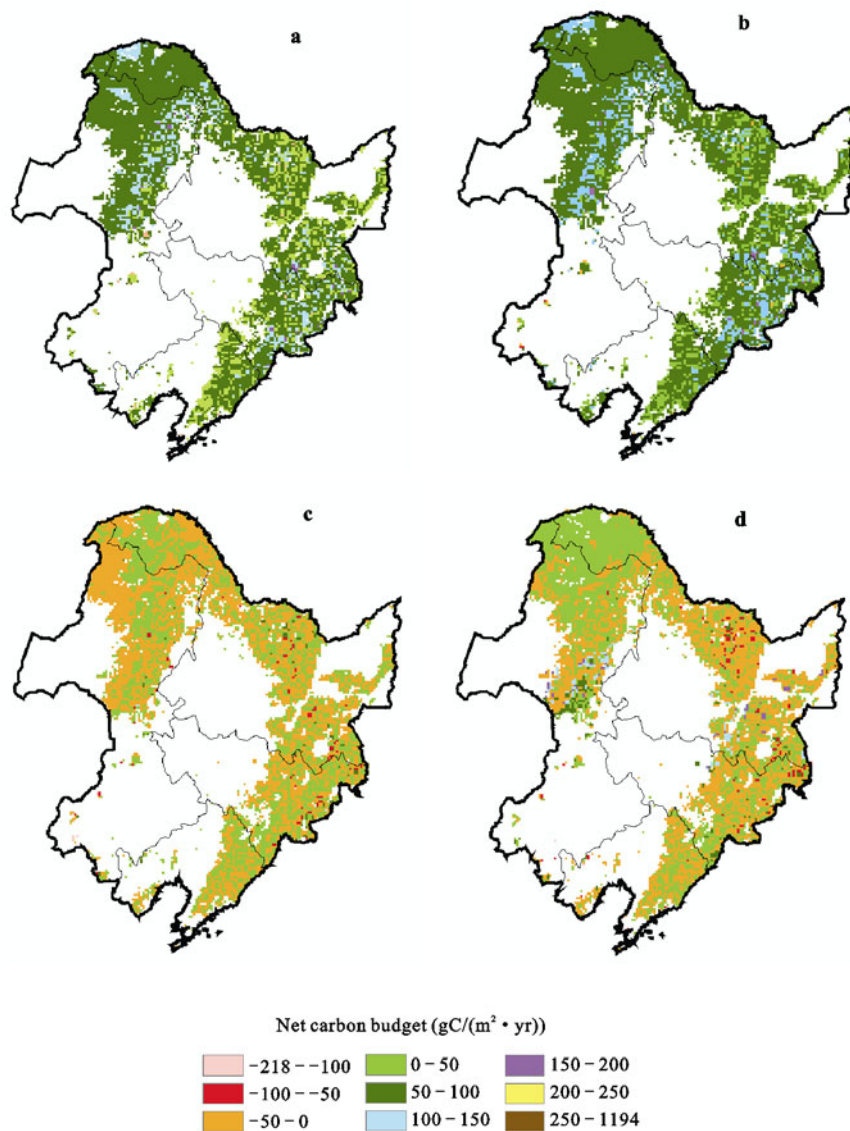
The changed net carbon budgets of forest ecosystems in the northeastern China were simulated under different climate scenarios (Fig. 6). Under the scenario of a 3°C increase in temperature and no change in precipitation (T3P0) or a 3°C increase in temperature and a 20% increase in precipitation (T3P2), the carbon budgets remarkably increased in most of the study area, with maximal increases of 230 gC/(m²·yr) and 232 gC/(m²·yr), respectively. The average value of the increase was 64.6 gC/(m²·yr) and 67.3 gC/(m²·yr), respectively, and the standard deviation was 27.0 gC/m² and 27.7 gC/m², re-

spectively. However, under the scenario of no change in temperature and a 20% increase in precipitation (T0P2) or no change in temperature and a 20% decrease in precipitation (T0P-2), the carbon budgets increased or decreased accordingly, with an average increase of 1.6 gC/(m²·yr) and an average decrease of 0.5 gC/(m²·yr), and a standard deviation of 20.5 gC/m² and 42.6 gC/m², respectively, again indicating that carbon budgets were more sensitive to the increase of air temperature than the change of precipitation.

5 Discussion

5.1 Carbon sinks effect of forest ecosystems in northeastern China

From 1981 to 2002, the forests played a positive role in absorbing carbon dioxide in the northeastern China, and every year they absorbed 0.017 PgC carbon dioxide on average, and this was consistent with the estimates reported by Tan *et al.* (2007), who suggested that the forest biomass carbon stock in Northeast China had increased by 7% from 1982 to 1999 by using forest inventory datasets for three inventory periods of 1984–1988, 1989–1993, and 1994–1998, and NOAA/AVHRR Normalized Difference Vegetation Index (NDVI) data. However, our estimate was also clearly lower than the carbon sink capacity of eastern US forests stimulated by Turner *et al.* (1995), who found that the forest ecosys-



- a, Daily temperature increased by 3°C and precipitation unchanged (T3P0);
 b, Daily average temperature increased by 3°C and precipitation increased by 20% (T3P2)
 c, Daily average temperature unchanged and precipitation increased by 20% (T0P2)
 d, Daily average temperature unchanged and precipitation decreased by 20% (T0P-2)

Fig. 6 Simulated spatial change of net carbon budget at different climate scenarios in northeastern China

tem could absorb 0.079 PgC every year in the eastern United States. One of the main reasons we believe is the difference in vegetation types (phenology), age, and succession stages between the forests between these two regions. In addition, our simulated carbon sink, mostly $300\text{--}700 \text{ gC}/(\text{m}^2 \cdot \text{yr})$, it is higher compared with the published $169\text{--}187 \text{ gC}/(\text{m}^2 \cdot \text{yr})$ in the Changbai Mountains by eddy covariance measurement over an old, temperate mixed forest in northeastern China (Guan *et al.*, 2006). We think that the difference is mainly caused by research methods and used data. Firstly, one of the main

reasons we believe for the higher carbon stock is that large areas of evergreen coniferous forests found in the northeastern China tend to provide carbon sinks all year round. Meanwhile, due to recent human disturbances, forests in the northeastern China are generally younger and in earlier stage of vegetation succession. It was demonstrated that younger forest generally had a higher potential for carbon uptake than older forests related to faster growth and stronger net photosynthesis (Tilman *et al.*, 2001). However, the eddy covariance measurements of the forests in the Changbai Mountains in China can

only on behalf of old forests observations. Both autotrophic respiration and heterotrophic respiration of these old forests are bigger, and the carbon budgets are corresponding smaller. Secondly, the FORCCHN model is used in our study, which limits the user to $10\text{ km} \times 10\text{ km}$ spatial resolution, and the simulations and a variety of environmental factors are assumed to be uniform in every grid, which is different from previous forest inventory studies. So it is difficult to compare the simulated values with observed values within the same scale. In addition, our simulation depends on the existing forest carbon pool and soil carbon pool, which has some uncertainty. As we know, the carbon pool and carbon density of forest ecosystems in China are considerably different from region to region, and mostly concentrating in the northeast and southwest of China. In the eastern and southeastern plains, and the northern and northwestern hills of China, with high population density, the forest carbon pools are relatively small. Finally, with the accelerated pace of afforestation and forest management level, the forest coverage rate is gradually increasing. Therefore, in our study the rate of forest coverage from 1981 to 2002 is estimated as 13.54%, which may be higher than that of previous studies.

From the above we can know that the assessment of carbon budget forest ecosystems in the northeastern China is still relatively weak, and this is because at the ecosystem scale, vegetation and soil carbon storage are mainly affected by site conditions, vegetation type, stand age, community and soil structure, and so on; at the regional scale, mainly by climate, soil and human activities. Such spatial and temporal variability has great uncertainty in determining biomass and soil organic carbon. Meanwhile, in the sampling process, due to different sampling standard and computing approach, it is more prone to bring estimation bias. In addition, owing to insufficient data, poor systematic samples, uneven distribution of observation points, *etc.*, the parameters in models are not easy to determine, and thus the optimization and utilization of the models are also difficult, resulting in great uncertain assessment. So it is still necessary to continue to strengthen related research in this area.

5.2 Response of carbon budget to climate change in northeastern China

It was long discovered that coupling relations between

vegetation and climate were close and strong (Goldberg and Bernhofer, 2001). At the millennial scale, climatic change acts as the key factor governing vegetation distribution in many regions. The primary factors controlling the carbon budget of vegetation include temperature, precipitation, carbon dioxide concentration in the atmosphere, *etc.* Temperature increase can result in two aspects' effects on the productivity of the ecosystem in the northern mid-to-high latitude ecosystems. Firstly, the positive effect is that temperature rise might increase the length of the growing season of vegetation, improving photosynthesis efficiency, and enhancing the productivity of vegetation (Oechel *et al.*, 2000). Secondly, the negative effect may be that temperature rise can increase the consumption of water and bring on a water deficit in some biomes (Liang and Maruyama, 1995). However, in the high latitude regions of the Northern Hemisphere, the precipitation is higher than the evapotranspiration rate of vegetation in most cases, and the available heat is generally a limiting factor for plant growth, while a water deficit is not a major issue that limits plant growth and carbon uptake (Zhou, 1991; Li and Shi, 1998). In this study, we found that the net carbon budgets of forest ecosystems in the northeastern China were more sensitive to an increase of air temperature than the change of precipitation, which was similar to the stimulation results reported by Zhou (1991) and Li and Shi (1998).

Water availability can affect the carbon budget of vegetation through influencing water demand, water balance, and fix carbon in the process of photosynthesis. Janack (1997) suggested that water deficit would lead to a stomatal conductance decrease or closure, transpiration and photosynthesis descending markedly and biomass accumulation reducing. It had generally been considered that precipitation and the dynamics of soil water resulted from precipitation were key ecological factors in governing the net primary productivity of vegetation in aridity regions (Melillo *et al.*, 1993). However, this study found that moderate changes of precipitation had minor effects on the net carbon budget of forest ecosystems in the northeastern China.

Carbon dioxide that participates in photosynthesis as raw materials has a direct relation with the net primary productivity of vegetation, and at the same time it affects the net primary productivity through interactions with temperature, water demand, and nutriment demand,

and in the end it will affect the carbon budget (Meier and Fuhrer, 1997). It is an important and uncertain issue, however, whether or not carbon dioxide in atmosphere has a direct fertilization effect on tree growth. It was well known that the short and direct effects of carbon dioxide increase on tree growth increased photosynthesis rate, decreased heterotrophic and autotrophic respiration, reduced stomatal conductance, improved water use efficiency, and enhanced productivity (Emanuel *et al.*, 1985; Prince *et al.*, 2000). However, Smith and Shugart (1993) suggested that the photosynthesis rate was likely to decline to its original level if the tree was always exposed under a high carbon dioxide concentration. So far, no experiment has proved that the carbon dioxide increase has long-term and direct effects on trees or ecosystems. Mohan *et al.* (2007) suggested through a model simulation that the effect of increasing carbon dioxide on an ecosystem was less than that of increasing carbon dioxide on an individual tree, and he also found that there was no effect of increasing carbon dioxide on an ecosystem at all in some cases.

Based on recent research progresses and with the consideration of the complexity and uncertainty of the carbon dioxide fertilization effect, we simulated the annual net carbon budget with the improved FORCCHN model. However, the current simulation did not consider the effect of carbon dioxide on the carbon budget of forests, instead, it only came down to the possible influence of temperature and precipitation on the net carbon budget of forest ecosystems in the region. These complex processes and interactions will be addressed in the next version of the model while biogeochemical modules are added.

6 Conclusions

The forest carbon budget model FORCCHN, which was improved and applied through adding variables and modules of precipitation (rainfall and snowfall) interception by tree crown, understory plants and litter, had a good performance in simulating the carbon budget of forest ecosystems in the northeastern China. The forest ecosystems played a positive role in absorbing carbon dioxide from 1981 to 2002. However, the capability of absorbing carbon was slightly declining. As for the average spatial distribution of net carbon budgets, a majority of the regions were carbon sinks, with a greatest

carbon sink in several densely forested areas of the south of Liaoning Province. Several scattered areas in the Heilongjiang Province and the Liaoning Province were identified as carbon sources. We also found that the net carbon budgets of forest ecosystems in the northeastern China were more sensitive to an increase of air temperature than the change of precipitation. The carbon budget enhanced rapidly under scenario of combining a 20% increase in precipitation and a 3°C increase in air temperature; by contrast, minimal changes were found under scenarios of no change in air temperature and no increase or no change in precipitation. However, the mechanisms of the impacts of climate change on the net carbon budget were still unclear. Increasing nitrogen and phosphorus deposition, climate changes, and the regrowth of forests and afforestation, might be possible mechanisms as well.

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