



Quantifying the response of forest carbon balance to future climate change in Northeastern China: Model validation and prediction

Changhui Peng^{a,c,*}, Xiaolu Zhou^a, Shuqing Zhao^{a,b}, Xiangping Wang^b, Biao Zhu^b, Shilong Piao^b, Jingyun Fang^b

^a Institute of Environmental Sciences, Department of Biology Sciences, University of Quebec at Montreal, Case postale 8888, Succ Centre-Ville Montreal, QC Canada H3C 3P8

^b Department of Ecology, College of Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China

^c Ecology Research Section, Central-South University of Forestry & Technology, Changsha, Hunan 410004, China

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ABSTRACT

In this study, we report on the validation of process-based forest growth and carbon and nitrogen model of TRIPLEX against observed data, and the use of the model to investigate the potential impacts and interaction of climate change and increasing atmospheric CO₂ on forest net primary productivity (NPP) and carbon budgets in northeast of China. The model validation results show that the simulated tree total volume, NPP, total biomass and soil carbon are consistent with observed data across the Northeast of China, demonstrating that the improved TRIPLEX model is able to simulate forest growth and carbon dynamics of the boreal and temperate forest ecosystems at regional scale. The climate change would increase forest NPP and biomass carbon but decrease overall soil carbon under all three climate change scenarios. The combined effects of climate change and CO₂ fertilization on the increase of NPP were estimated to be 10–12% for 2030s and 28–37% in 2090s. The simulated effects of CO₂ fertilization significantly offset the soil carbon loss due to climate change alone. Overall, future climate change and increasing atmospheric CO₂ would have a significant impact on the forest ecosystems of Northeastern China.

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1. Introduction

In the past few decades, both observational and modeling studies have demonstrated that forest ecosystems in the middle and high latitudes of the Northern Hemisphere act as large carbon sinks of atmospheric carbon dioxide (Tans et al., 1990; Dixon et al., 1994; Ciais et al., 1995; Fan et al., 1998; Schimel et al., 2001; Fang et al., 2001; Pacala et al., 2001). These studies are mainly conducted from North America and European countries (e.g. Kauppi et al., 1992; Ciais et al., 1995; Goodale et al., 2002; Jackson and Schlesinger, 2004). Using national forest resource inventories, several recent studies have revealed that the planted forests in East Asia also play a substantial role in sequestering carbon dioxide (Fang et al., 2001; Choi et al., 2002; Fang et al., 2005). Bousquet et al. (1999) also suggested that a significant carbon sink is located in northern Asia based on the inverse modeling approach. However, the location, magnitude and mechanisms of these sinks are still debated due to the diversity and complexity of forest ecosystems (Schimel et al., 2001; Goodale et al., 2002; Houghton, 2003). The forest growth enhanced by changes in climate and atmospheric CO₂ and land use was believed to account for

a large part of the terrestrial carbon sinks (IPCC, 2001). Many recent studies based on future climate change scenarios derived directly or indirectly from general circulation model (GCM) simulations suggested that changes in atmospheric CO₂ concentration and future climate are likely to significantly alter future forest production, succession, composition, and carbon balance of terrestrial ecosystems. The northern forest ecosystems are especially vulnerable to climate change, due to the longevity of trees and the extent of the expected climate change within their life span (Goulden et al., 1998; IPCC, 2001). The potential impacts and interactions of climate change and increasing CO₂ on northern forest ecosystems have been one of high priorities in the global carbon cycles and climate change impacts research (IPCC, 2001; GCP, 2004).

The forest ecosystems in northeast China play an important role in the national carbon budget because they comprise more than 30% of total forest area in China (Fang and Chen, 2001), including the southern boundary boreal forests of the Eurasia in Daxing'anling region of Heilongjiang Province and Inner Mongolia, which are specially 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 China's net primary productivity (Jiang et al., 1999; Ni et al., 2001; Ni, 2003; Fang et al., 2003; Piao et al., 2005; Zhao and Zhou, 2005), forest biomass (Fang et al., 1998; Fang et al., 1999; Fang et al., 2001; Li et al., 2004; Pan et al., 2004), soil carbon storage (Fang et al., 1996; Wang et al., 2003; Wu et al., 2003a,b), possible

* Corresponding author. Institute of Environmental Sciences, University of Quebec at Montreal, Case postale 8888, Succursale Centre-Ville, Montréal, Canada H3C 3P8. Tel.: +1 514 987 3000x3041; fax: +1 514 987 4718.

E-mail address: peng.changhui@uqam.ca (C. Peng).

responses to past climate change (Peng and Apps, 1997); interannual climate variability (Cao et al., 2003; Piao et al., 2003, 2005) and future climate change (Xiao et al., 1998; Gao et al., 2000; Ni et al., 2001). Recent estimates of forest biomass carbon in China suggested that Chinese forest ecosystems were acting as a carbon sink during the past decades (Fang et al., 2001). However, the forest carbon sink is not permanent and likely to be altered with the changes in climate and increasing CO₂. Fang et al. (2003) and Piao et al. (2005) also showed that China's terrestrial NPP has been significantly increased due to the increases in temperature, precipitation and CO₂ concentration and the largest increases in NPP were observed in broad-leaf and needle-leaf mixed forests in northeast of China. To date, few studies have been conducted to investigate the potential impacts of future climate change and increasing CO₂ on forest productivity and carbon balance of forest ecosystem in northern China (Li, 1995; Shao, 1996; Gao and Zhang, 1997; Ni, 2002). However, the study of Li (1995) was limited by the empirical statistic approach based on climatic data and vegetation distribution. Although the gap-based modeling approach by Shao (1996) and Shao et al. (2001) and process-based modeling approaches by Gao and Zhang (1997) and by Ni (2002) provided an improved understanding of the response of forests to future climate change, they were limited by the selection of small area of gap (Shao, 1996; Chen, 2002), or transect (Gao and Zhang, 1997) or only boreal forests (Ni, 2002) in northeast of China. These previous studies are useful but did not provide a big picture of potential impacts of future climate change and increasing CO₂ on forest carbon budgets in northeastern China at regional scale. Another common challenge with the climate change impact studies and regional-scale modeling is model validation. This is mainly due to the limited available field measurements of forest growth and yield, NPP, biomass and soil carbon at appropriate scale. Thus, most models have only been compared with limited sites or plots measurements (Gao and Zhang, 1997; Xiao et al., 1998; Ni, 2002; Cao et al., 2003).

To accurately quantify the dynamics of forest ecosystem carbon sinks and reduce the uncertainty in estimating forest carbon budgets under a changing climate, we need to take into account the response of forest carbon pools and its dynamics to future projected climate and

increasing CO₂. The gaps that exist are in predicting the impacts of future climate change and increasing CO₂ on forest productivity and carbon sinks at regional scale. CO₂ fertilization, via its effects on terrestrial carbon uptake, remains large uncertain components of the global carbon cycles (Norby et al., 2005; Matthews, 2007; Piao et al., 2008). Process-based forest simulation models are powerful tools to help in understanding the complex effects and interactions of climate change and on increasing CO₂ on forest productivity and carbon budgets (Cao and Woodward, 1998; Cramer et al., 2001; Matthews, 2007). Cramer et al. (2001) have reported a global-scale analysis of the effects of climate change and elevated CO₂ on terrestrial ecosystem productivity. Unfortunately, predictions from such broad-scale modeling cannot be adequately validated because of a lack of field measurements. The objectives of this study are to: (1) validate the TRIPLEX1.0 model (Peng et al., 2002) using a comprehensive ground observations and measurements of forest growth, NPP, biomass and carbon in vegetations and soils; and (2) simulate the temporal and spatial response of NPP and carbon balance under projected future climate change and increasing CO₂ scenarios in 21st century.

2. Methods and data

2.1. Study area

The study was carried out in forested lands of northeast China (Fig. 1) located in the southern edge of Eurasia boreal forests and consists of Heilongjiang, Jilin and Liaoning provinces, and the eastern part of Inner Mongolia Autonomous Region. The study region, covering about 1,240,000 km² (about 12.9% of the total country area) with the approximate latitudinal range of 38–54°N and longitudinal range of 110–136°E, contains 4 major forest types in East Asia including temperate and boreal conifer, *Larix*, deciduous, and mixed forests (Zhou, 1997). Major soil types include the dark-brown earths, brown coniferous forest soils, calcic chernozems and meadow soils (ISSCAS, 1986). This study area was selected not only because there exists forest inventory, forest sample plots and soil data for

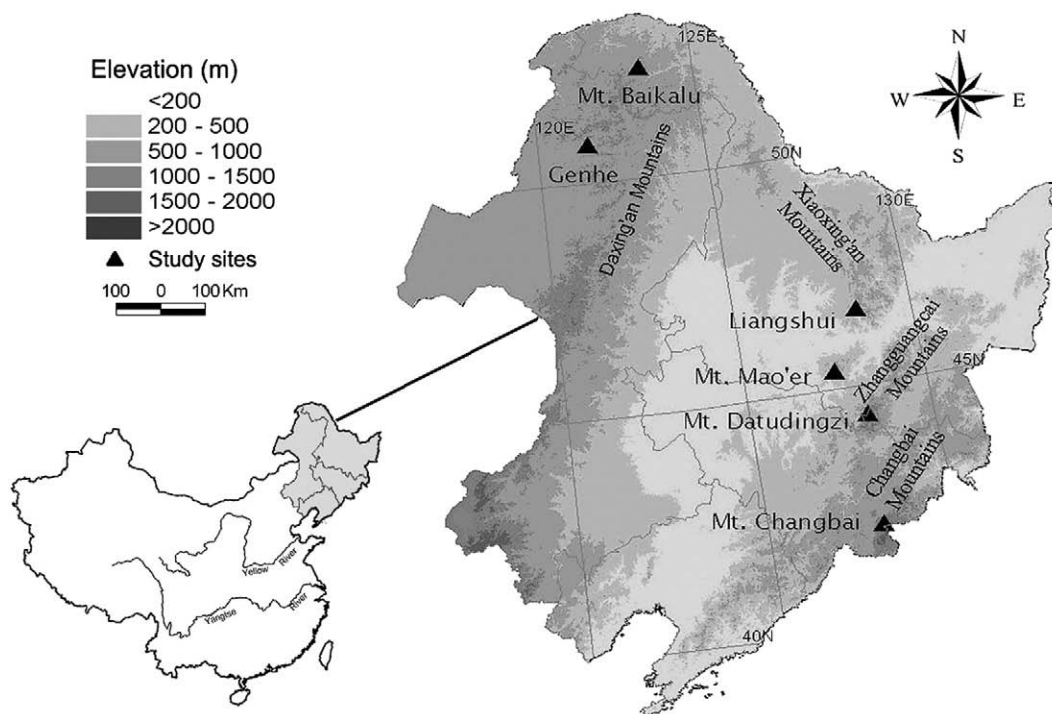


Fig. 1. Study area. Solid triangles denote 6 site locations where data were measured in 70 plots.

testing TRIPLEX1.0 model but also because this area represents a pronounced climatic gradient through the boreal forests in Mt Baikal to mixed forests in Mt Changbai and an ideal region for exploring the relationship between forests and climates and carbon dynamics under future climate change. 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 temperate, temperate 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 -7.3 to 12 °C and precipitation ranges from 180 to 926 mm (with 1336 mm in the high elevation in the eastern part) (Piao et al., 2003). 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 (Fang et al., 2001, Ni, 2002; Houghton, 2003; Wang et al., 2006). The carbon storage in these forested area accounts for more than 27.5% of the total carbon stock of China's forests (Fang et al., 2001; Zhu, 2005). In this study, we did not consider the agriculture region located in central part of northeast of China (Fig. 1).

2.2. Model description

The TRIPLEX1.0 model (Peng et al., 2002) is a process-based hybrid model of forest growth and carbon and nitrogen dynamics (Fig. 2), which integrated functions used in three well-established models, 3-PG (Landsberg and Waring, 1997), TREEDYN3.0 (Bossel, 1996), and CENTURY4.0 (Parton et al., 1993). The structure of the TRIPLEX model includes 4 submodels: (1) Forest production. It estimates PAR and GPP including above- and below-ground biomass. The PAR was calculated as a function of the solar constant, radiation fraction, solar height, and atmospheric absorption. Monthly PAR received by the forest canopy is

estimated using cloud ratios. The model calculates monthly GPP from received PAR, mean air temperature, vapour pressure deficit, soil water, percentage of frost days, and leaf area index; (2) Forest growth and yield. The major variables of tree growth and yield were derived from biomass increment. The key variable is the increment of tree diameter, which was calculated using a function of stem wood biomass increment (Bossel, 1996); (3) Soil carbon and nitrogen. The dynamics of soil carbon and nitrogen were simulated for the litter and soil pools. This submodel was based on CENTURY soil decomposition modules (Parton et al., 1993), Decomposition rates of soil carbon for each carbon pool were calculated as functions of maximum decomposition rates, effects of soil moisture, and soil temperature; and (4) Soil water balance. This component is a simplified water budget module that calculates monthly water loss through transpiration, evaporation, soil water content, and snow water content. It is a part of soil water submodel of the CENTURY model for simulating water balance and dynamics. The model components of TRIPLEX1.0 are presented by class objects using objective-oriented programming (OOP) and C++ (Liu et al., 2002). The user-friendly interface provides flexibility in input data, output results, and analysis of simulation results.

The model input was designed simply including three parts, climate data, soil texture, and vegetation conditions. In TRIPLEX1.0 (Fig. 2), carbon allocation functions in 3-PG (Landsberg and Waring, 1997) were utilized by parameterizing based on field data and empirical coefficients (Zhou et al., 2006); biomass growth rate was calculated from annual increments; soil water, carbon and nitrogen were calculated by the corresponding modules in the CENTURY4.0 model (Parton et al., 1993). The detailed description of the TRIPLEX1.0 model feature, structure, mathematical representation, sensitivity analysis and building strategy is previously provided by Peng et al. (2002) and Liu et al. (2002), and Zhou et al. (2004). To date, the TRIPLEX1.0 has been successfully calibrated and validated against age-

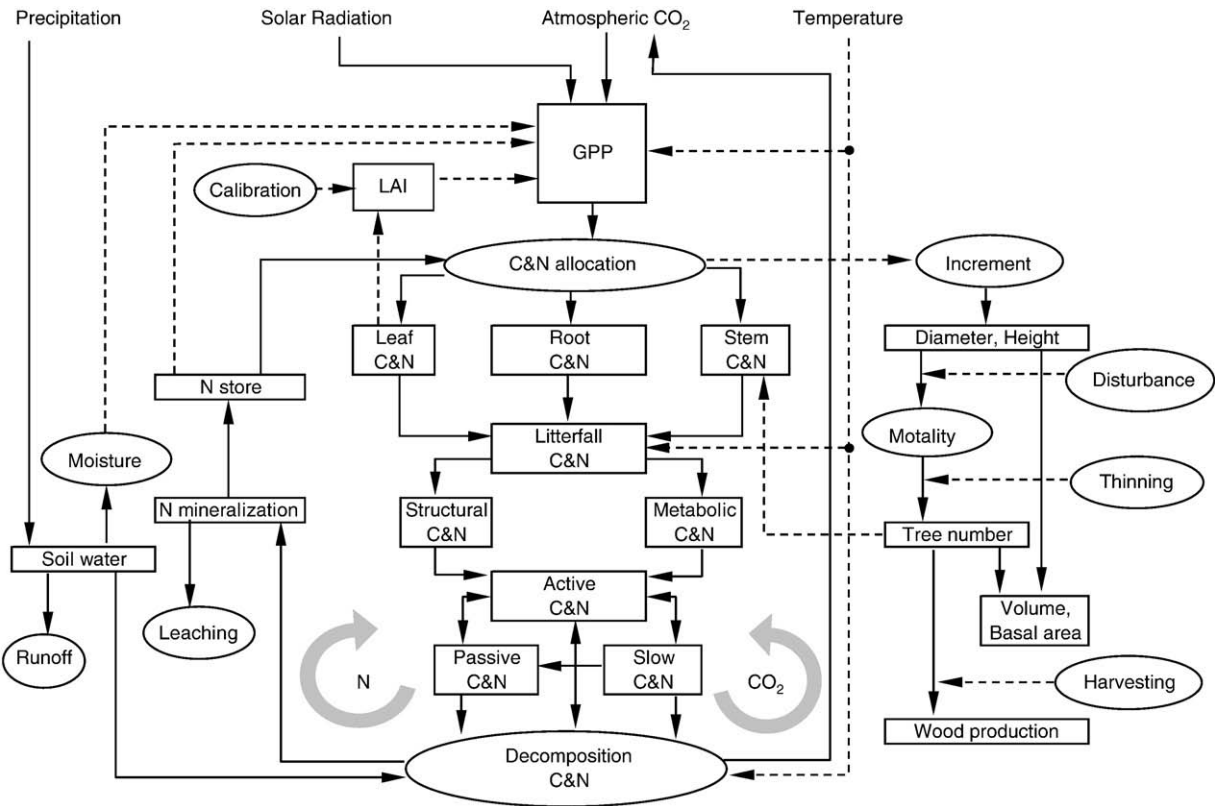


Fig. 2. The structure of forest growth and carbon simulation model TRIPLEX1.0 (modified from Peng et al., 2002). Rectangles represent key pools or state variables, ovals represent core simulation processes, point lines represent controls, and solid lines represent flows of carbon (C), nitrogen (N), water, and the fluxes between the forest ecosystem and external environment. Two arrow cycles refer to feedbacks.

dependent growth measurement from 12 permanent sample plots (PSP) for jack pine stands in northern Ontario, Canada (Peng et al., 2002), for boreal mixedwood in the Lake Abitibi Model Forest (Zhou et al., 2004, 2005a,b), and other boreal tree stands in BOREAS sites of central Canada (Zhou et al., 2004). However, the present study presents our first attempt to test the TRIPLEX1.0 and apply it for studying forest ecosystems in northeast of China.

2.3. Model modification and adaptation for simulating effects of CO₂ fertilization

In the earlier version of TRIPLEX1.0 (Peng et al., 2002), the calculation of NPP was directly derived from GPP based on the a fixed ratio of NPP/GPP, although NPP/GPP ratio may be affected by an increased temperature and elevated CO₂ concentration (Gifford, 1995; Dewar et al., 1999; Tjoelker et al., 1999; Cheng et al., 2000). In this study, the NPP, like in many other process-based terrestrial carbon models (Cramer et al., 2001), is estimated by subtracting autotrophic respiration (R_a) from GPP. The NPP allocation to leaf, stem and roots are adopted from the improved dynamics functions of Zhou et al. (2006). Net ecosystem productivity (NEP) is difference between NPP and heterotrophic respiration (R_h). The growth respiration is calculated based on respiration coefficients and GPP and maintenance respiration is calculated using the Q_{10} function (Q_{10} value = 2.0)

multiplied by the biomass of each plant component (leaf, sapwood, and root) (Ryan, 1991). The R_h is estimated within TRIPLEX1.0 as the sum of all respiration fluxes of dead organic matter which equivalent to the net decomposition release of carbon from litter and soil pools described in CENTURY (Parton et al., 1993).

The effects of increased growth under elevated CO₂ condition, known as the CO₂ fertilization effect, are often cited as one of the major mechanisms explaining the missing C sink (IPCC, 2001). Field and laboratory experiments show that the potential effects of increased atmospheric concentration of CO₂ on ecological process include (1) a direct effect on C availability by stimulating photosynthesis and reducing photorespiration (Bazzaz, 1990; Ceulemans and Mousseau, 1994; Saxe et al., 1998; Norby et al., 1999), (2) a decrease in stomatal conductance (Wong, 1979; Morrison and Gifford, 1984), which reduces the transpiration rate per unit leaf area, (3) a decrease in plant N concentration in C3 species (Schmitt and Edwards, 1981), and (4) an increase in water and nitrogen use efficiency (NUE) in both C3 and C4 plants (Owensby et al., 1993; Wullschlegel et al., 2002). Increases in atmospheric CO₂ have increased plant production of a wide variety of species by an average of 23%–33% (Kimball, 1983; Saxe et al., 1998; Norby et al., 2005). The current literature indicates a significantly larger average long-term biomass increment under elevated CO₂ for both conifer and deciduous trees in studies not involving stress components (Saxe et al., 1998).

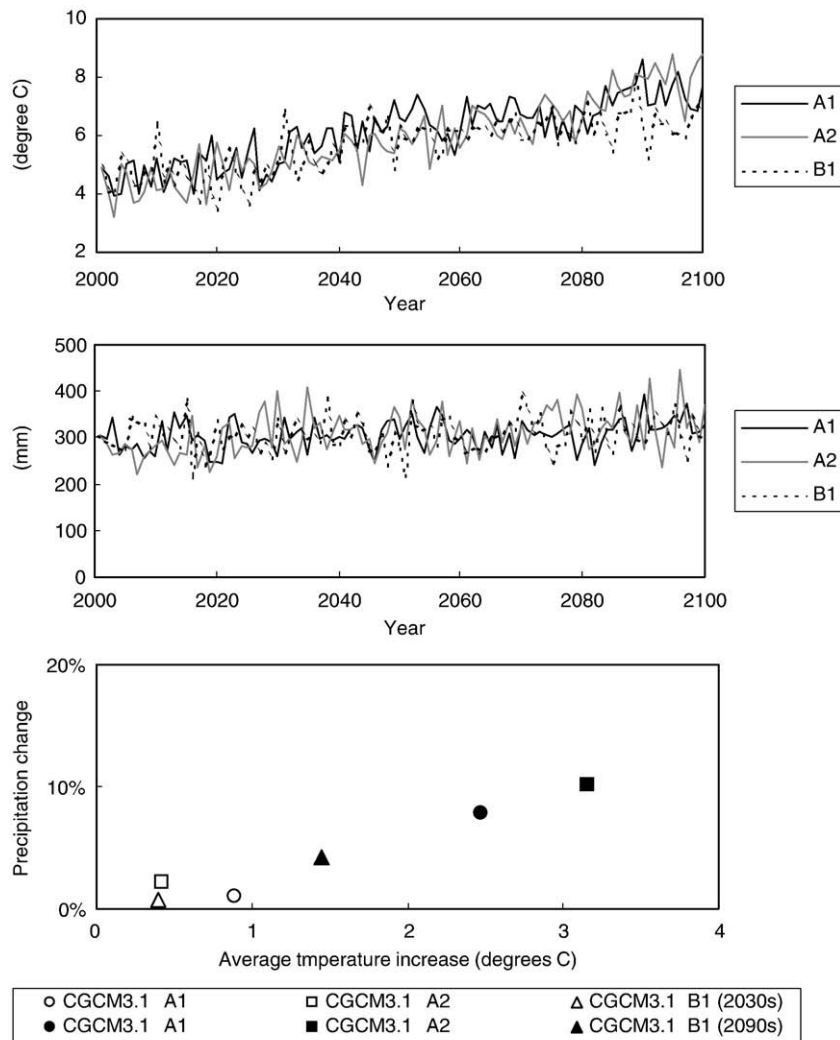


Fig. 3. Future trends of temperature (a) and precipitation (b) projected by Canadian coupled general circulation model (CGCM3.1) under the scenarios of A1, A2, and B1 (see Table 1) at center of northeast China (weather station near Harbin city at the latitude of 45.75°N and longitude of 126.77°E). (c) refers to relative changes in future climate.

Following the similar approach of CENTURY (Parton et al., 1995; Peng and Apps, 1998, 1999) and other terrestrial biogeochemical models (King et al., 1995; Friedlingstein et al., 1995), the effect of CO₂ fertilization on plant production is quantified using a logarithmic response function (Gifford, 1979; Goudriaan, 1992; King et al., 1995; Friedlingstein et al., 1995).

$$NPP_E = NPP_0 * (1 + \beta \ln(CO_{2E} / CO_{20})) \quad (1)$$

Where NPP_E and NPP₀ refer to net primary productivity in enriched (CO_{2E}) and control (CO₂₀) CO₂ environments respectively. β is an empirical parameter which ranges between 0 and 0.7. According to King et al. (1995), we used $\beta=0.34$ for boreal and 0.43 for temperate deciduous forest in northeastern China in our calibration of TRIPLEX1.0. The above effects can be taken into account in TRIPLEX1.0 model simulations of climate change effects by selecting the enriched CO₂ option. This option can be implemented with either a constant CO₂ concentration or with a linear ramp with annual increments from an initial concentration to a final concentration. The NPP parameter under a doubled CO₂ (from 350 to 700 ppm) climate was also adjusted to achieve 20–30% of increase in NPP (Eq. (1)). These effects were taken into account in the TRIPLEX1.0 simulation of climate change and CO₂ fertilization effects by increasing the maximum potential monthly production of boreal forests by a factor of about 1.24, which is consistent with recent results of 21–25% of increase in NPP under elevated CO₂ in four free-air CO₂ enrichments experiments (Norby et al., 2005) and the 30% increase in the average long-term biomass of conifers under elevated CO₂ reported by Saxe et al. (1998) in a summary of recently published literature.

2.4. Input data

2.4.1. Climate Input

The historical climate data is available for the period from 1950 to 1999 based on observations at 102 weather stations in northeast China (Piao et al., 2003). We used the monthly mean temperature and precipitation averaged over 1990–1999 as baseline for the 1990s. In this study, we used projected future transient climate change scenarios derived from the latest outputs of Canadian coupled general circulation model (CGCM3.1). The climate change scenarios were conducted in support of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) (IPCC, 2005). The TRIPLEX1.0 model simulations were based on the following three scenarios (Fig. 3): (1) Scenario A2 that describes a heterogeneous world with higher emission. In A2 run of CGCM3.1, CO₂ concentration increases from 350 in 2000 to 850 ppm in 2100, and air temperature increases 4 °C in the same period. (2) Scenario B1 that describes the sustainable development and the introduction of resource-efficient technologies with lower emission. In B1 run, CO₂ concentration increases from 350 in 2000 to 550 ppm in 2100, and air temperature increases 2 °C in the same period. (3) Scenario A1 emphasizes a balance across all energy sources with a moderate emission, which increases from 350 to 700 ppm in 21st century, and air temperature increases 3 °C in the same period. These three scenarios (A2, A1 and B1) were chosen because they have distinct gradients of CO₂ concentration and emissions. Fig. 3 summarizes changes in monthly mean temperature and precipitation for 2030s and 2090s. Because the outputs of CGCM3.1 are at a 3.75° × 3.75° spatial resolution, CGCM3.1 outputs were then downscaled by interpolating into 10 × 10 km² for monthly temperature and precipitation in order to be consistent with the observed mean monthly temperature and precipitation over 1990–1999 (Piao et al., 2003).

2.4.2. Vegetation and soil texture

The information of vegetation type and soil texture was derived from Chinese vegetation distribution map (1:4,000,000) developed by IGCAS (1996). The vegetation type was categorized as 5 types, such

as boreal conifer, temperate conifer, mixed, deciduous, and shrub-grass (Fig. 4). The shrub regions were not included in the simulation of TRIPLEX1.0 in this study because the model is forest-based model and has obvious limitations for simulating shrub-grassland ecosystems. The remotely sensed LAI distribution map of 1999 for the northeast of China derived from Deng et al. (2006) was used as initial condition to constrain the GPP calculations in the model simulation (Table 1). The LAI estimate, retrieval methodology, algorithms, and validation were described by Deng et al. (2006). Soil texture including percentage of sand, silt and clay, bulk density and soil organic carbon were derived from a digital version of 1:4,000,000 soil maps of China, which is based on the second national soil survey (NSSO, 1995a,b, 1996, 1998). We used both vegetation and soil information as inputs for TRIPLEX1.0 baseline simulations. The regional-level estimation based on all simulation results of every stand was performed by converting stand-level maps to regional map at 10 × 10 km² grid cell using GIS (converting vector to raster map in ArcGIS).

2.5. Parameterization and initialization

To provide a robust test of TRIPLEX1.0, most of the general and non-site-specific parameters from previous studies (Peng et al., 2002; Zhou et al., 2004, 2005a,b) were left unchanged (see Table 2). These include parameters for photosynthetically active radiation (PAR), minimum, maximum, and optimum temperature for tree growth, stomata and canopy conductance, specific leaf area, initial nitrogen for tree growth, turnover rates for leaves and fine roots, lignin–nitrogen ratio and lignin fraction for leaf, fine and coarse roots as well as fraction of soil water flow. Some of the new parameters of interest that were adopted and adjusted from model default values to better represent the forest ecosystems in northeast of China in this study are listed in Table 3.

2.6. Validation data

To test the ability of TRIPLEX1.0 to simulate forest growth and yield, NPP, biomass, and soil carbon storage in northeast of China, we used the data obtained from various sources (Table 1) including: (1) 133 observed NPP sites selected from published national NPP database (Luo, 1996; Jiang et al., 1999; Ni et al., 2001); (2) tree biomass and volumes are measured from 70 forest plots and provided by Zhu (2005); (3) published soil carbon data (Yang and Li, 2003; Zhu, 2005), and (4) tree total volume obtained from Luo (1996). The observed

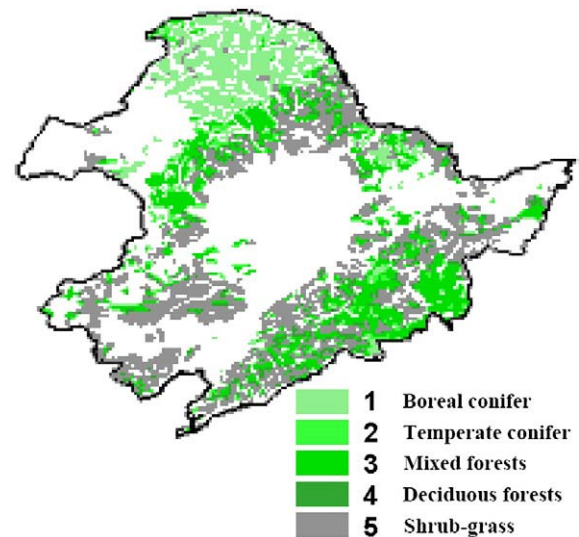


Fig. 4. Distributions of 5 major forest ecosystem types. 5 major forest ecosystems include (1) boreal conifer; (2) temperate conifer; (3) mixed; (4) deciduous and (5) shrub-grass (which is not used in the model simulations).

Table 1
Various data used as inputs and model validation for TRIPLEX1.0 in this study.

Data source	Use	Reference
<i>Historical and future climate</i>		
CGCM3.1(74) outputs for the period from 2001 to 2100, under three scenarios: (a) A2, Temperature and CO ₂ increase 4 °C and 350–850 ppm; (b) A1, Temperature and CO ₂ increase 3 °C and 350–700 ppm; (c) B1, Temperature and CO ₂ increase 2 °C and 350–550 ppm	Model inputs for simulating future carbon dynamics from 2000 to 2100	IPCC (2005)
Observations of monthly temperature and precipitation for the period from 1990 to 1999 (102 weather stations in northeast China)	Climate input for model spin up and adjustment for GCM-modeled values, parameterization and validation for TRIPLEX1.0.	Piao et al. (2003)
<i>Vegetation and LAI distribution</i>		
Chinese vegetation distribution map (1:4,000,000)	Vegetation input for model test and future prediction of carbon dynamics assuming the same vegetation cover type	IGCAS (1996)
Remote sensing based estimate of LAI	Model input for calculating GPP	Deng et al. (2006)
<i>Soil texture</i>		
Chinese soil texture category map (1:14,000,000)	Parameterization of TRIPLEX1.0.	NSSO (1995a,b, 1996, 1998)
<i>Field observations across northeastern China</i>		
Measurements of tree total volume and biomass at 70 plots	Validation of TRIPLEX1.0 for tree volume and biomass	Zhu (2005)
Tree volume collected from 111 forest farms	Validation of TRIPLEX1.0 for tree volume	Luo (1996)
Measurements of NPP at 133 Sites	Validation of TRIPLEX1.0 for NPP	Luo (1996), Ni et al. (2001)
Soil carbon	Validation of TRIPLEX1.0 for soil carbon	Zhu (2005), Yang and Li (2003)

forest NPP data sets are obtained from the most comprehensive database originally compiled by the Ph.D. dissertation of Luo (1996) and published by Ni et al. (2001). The database includes over 2000 measurements from about 690 forest stands and 17 major forest types across China. These 70 forest plots of Zhu (2005) were measured from 2000 to 2004 across 6 sites (including Mt Baikalu, Genhe, Liangshui, Mt Maoer, Mt Datudingzi, and Mt Changbai) located in northeast of China (Fig. 1). 111 total tree volume datasets, collected by Luo (1996) from 111 forest farms located across northeast of China under different climate conditions, were regrouped according to our major forest types and used for testing model simulation on tree volume.

2.7. Simulation strategy and climate change scenarios

The historical climate data including monthly mean temperature and precipitation averaged over 1990–1999 (Piao et al., 2003) were used as model input to spin up model simulation about 200 years so that soil carbon pools can arrive at equilibrium state. A number of CO₂-induced climate change scenarios have been generated and updated with various general circulation models (GCMs) in recent years [e.g., The Hadley Centre GCM in UK, Canadian GCM, CCSM3, GFDL and GISS in USA; CSIRO-MK3.0 in Australia, MIR-CGCM2.3 in Japan etc, IPCC, 2005]. Our objective in present study was to examine the sensitivity of carbon balances of northeast forests in China to potential climate change and the factors controlling the sensitivity, rather than to generate forecast of changes themselves. For this reason we chose to look at only one of latest available climate model of Canadian coupled

Table 2
Parameters used in the TRIPLEX1.0 for simulating northeastern China's ecosystems.

Parameter	Description	Note
<i>PAR</i>		
Absorp = 0.15	Atmospheric absorption factor	a
PARfactor = 0.47	Solar radiation fraction	c
<i>GPP</i>		
Sla = 6	Specific leaf area (m ² kg ⁻¹)	b
MaxCond = 0.02	Max canopy conductance (ml m ⁻² s ⁻¹)	i
StomCond = 0.005	Stomata conductance (ml m ⁻² s ⁻¹)	i
Blcond = 0.2	Canopy boundary layer conductance (ml m ⁻² s ⁻¹)	i
CoeffCond = -0.5	Coefficient for conductance to VPD	i
ExtCoef = 0.5	Radiation extinction coefficient	i
TaMin = 5	Min temperature for growth	a,d
TaMax = 40	Max temperature for growth	a, i
Topt = 15	Optimum temperature for growth	b
NitrogenFactor = 0.2	Nitrogen factor for tree growth, e.g., 0.2 denotes 20%	e
GamaR = 0.3	Fine roots turnover per year	g
GamaF = 0.12	Leaves turnover per year	h
<i>Tree growth</i>		
MiuNorm = 0.006	Normal mortality per year	f
MiuCrowd = 0.01	Crowding mortality per year	a
<i>Soil C and N</i>		
Lnr = 0.26	Lignin–nitrogen ratio	e
Ls = 0.215, 0.215, 0.255, 0.235, 0.255	Lignin for leaf, fine root, coarse root, branch, and wood	e
<i>Soil water</i>		
A1, A2, A3 = 15	Depth of layers 1, 2, and 3	e
AWL1, 2, and 3 = 0.5, 0.3, and 0.2	Relative root density for layers 1, 2, and 3	e
KF = 0.5	Fraction of water flow (except field capacity) to stream	Assumption
KD = 0.5	Fraction of water flow (except field capacity) to deep storage	Assumption
KX = 0.3	Fraction of deep storage water to stream	Assumption
AWater = 250.0	Max soil water (mm)	Assumption

^aBossel (1996); ^bKimball et al. (1997); ^cRyan et al. (1997); ^dLandsberg and Waring (1997). ^eThe values are given by CENTURY (Parton et al., 1993, Metherell et al., 1993); ^fSuggested by Bossel (1996), the stand mortality was assumed as the normal mortality (no canopy competition for light) plus crowding mortality; ^gSteele et al. (1997); ^hEstimated based on results (0.069–0.083 year⁻¹ in southern BOREAS area) of Gower et al. (1997); ⁱCoops et al. (2001).

general circulation model (CGCM3.1) with three climate changes scenarios (A2, A1, B1, see Table 1 and Fig. 3). We performed simulations to examine the sensitivity of northeast forest ecosystems

Table 3
Parameters used in the TRIPLEX1.0 for simulating different species in northeastern China.

Forest type	Temperate				Boreal		Note
	Conifer	Larix	Deciduous	Mixed	Larix	Deciduous	
Wood C density (t m ⁻³)	0.23	0.22	0.23	0.22	0.23	0.23	a
Crown/DBH	20	20	20	20	20	20	b
Canopy quantum efficiency (α _c)	0.05	0.06	0.06	0.06	0.06	0.06	c
Leaf fraction	0.05	0.025	0.025	0.05	0.025	0.025	d
Branch fraction	0.1	0.125	0.125	0.1	0.125	0.125	d
Wood fraction	0.7	0.65	0.65	0.7	0.65	0.65	d
Coarse root fraction	0.15	0.15	0.15	0.15	0.15	0.15	d
Fine root fraction	0.05	0.05	0.05	0.05	0.05	0.05	d

^a Estimation based on Alemdag (1984), Dixon et al. (1991), Dewar and Cannell (1992), Schroeder (1992), and Nabuurs and Mohren (1995).

^b Zhu (2005).

^c Estimation based on Waring and McDowell (2002), and Zhu (2005).

^d Estimation based on Feng et al. (1999).

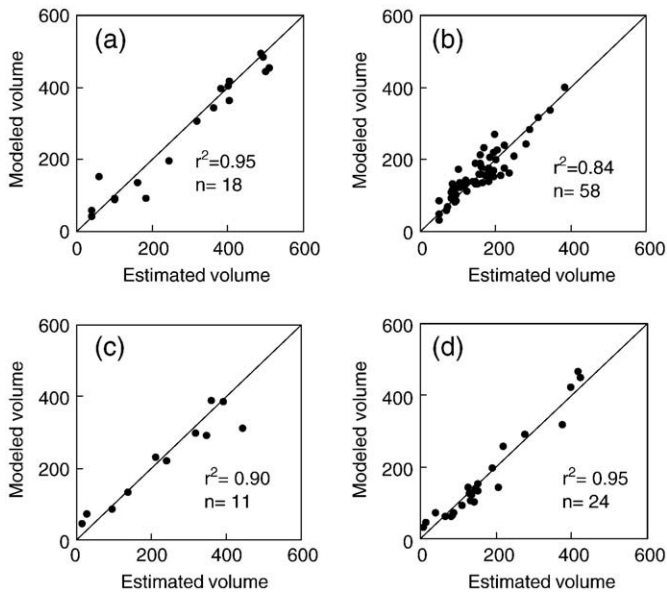


Fig. 5. Comparison between modeled and estimated volume (m^3). The volume was modeled using parameters listed in Tables 2 and 3. Estimated volume was based on the forest inventory in 111 sites. (a), (b), (c), and (d) denote temperate mixed, temperate deciduous, boreal conifer, and boreal/temperate *Larix*. Statistics of the comparison is summarized in Table 4.

to the following climate change effects: (1) effects of climate change without CO_2 fertilization (i.e. alteration to monthly mean temperature and precipitation based on the climate change scenarios from CGCM3.1 model, and (2) combined effects of climate change and CO_2 fertilization. The TRIPLEX1.0 runs continuously from the year of 1999 to 2100 and outputs of model (such as NPP, biomass, NEP, total carbon) are summarized and presented by three periods: (a) Baseline [1999]; (b) short-term (e.g. 2030s – average over 2030–2040); and (3) long-term (e.g., 2090s – averaged over 2090–2100).

3. Results

3.1. Model validation

Total tree volume is one of key variables used for evaluating forest growth and productivity for forest management. Process-based carbon dynamic models are rarely validated against traditional forest growth and yield data and are difficult to use as a practical tool for forest management (Peng et al., 2002; Zhou et al., 2005a,b). As shown in Fig. 5 and Table 4, the simulated tree volumes of TRIPLEX1.0 were consistent with observed data. The correlations between model simulations and observations are relatively high with $r^2=0.95$ for

Table 4

Model calibration: simulation errors of the TRIPLEX1.0 model applied to four forest types in northeastern China's forest ecosystems, comparing volume ($m^3 ha^{-1}$) between modeled values and forest inventory data collected from 111 forest farms (FRIC, 1999; Fang et al., 2001).

	Temperate mixed	Temperate deciduous	Boreal conifer	Boreal/temperate <i>Larix</i>
<i>n</i>	18	58	11	24
r^2	0.95	0.84	0.90	0.95
Se ^a	40.2	35.2	28.1	33.1
$\bar{\epsilon}^a$	15.2	1.8	14.6	4.3
Bias	5%	1%	6%	2%

^a Se, standard error of the predicted value for each observed value in the regression, which is a measure of the amount of error in the prediction for an individual observation; $\bar{\epsilon}$, average prediction error.

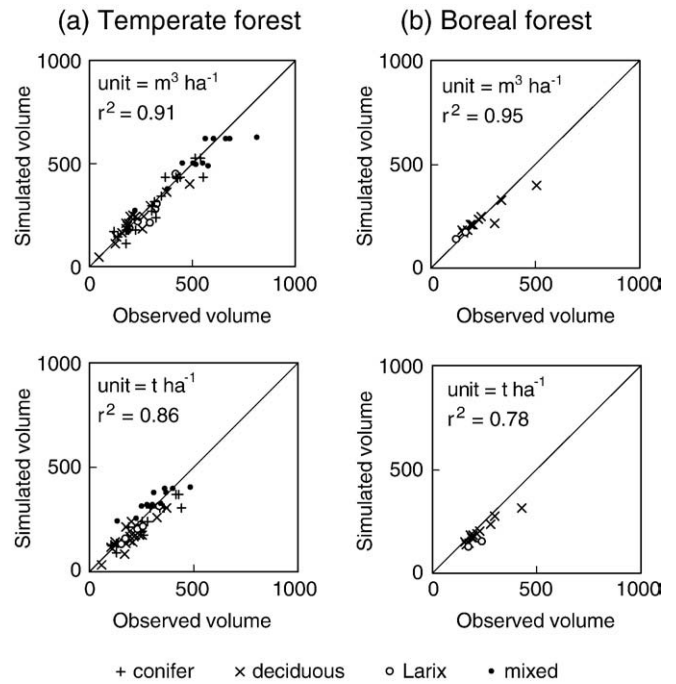


Fig. 6. Comparisons of tree volume and biomass between model simulations and observed data that were measured from 70 forest plots across 6 sites in northeast of China (as shown Fig. 1) during 2000–2004. Statistics of the comparison between model simulations and measurements are summarized in Table 5.

both temperate mixed and *Larix* forest, $r^2=0.90$ for boreal forests, and $r^2=0.84$ for temperate deciduous forests, respectively. The comparisons of tree volume ($m^3 ha^{-1}$) simulated by TRIPLEX1.0 with those field data measured from 70 forest plots for both temperate and boreal forests show good agreement (Fig. 6 and Table 5). The mean coefficient of determination (R^2) for tree volume is 0.91 for temperate and 0.95 for boreal forest. The simulated errors are relatively small with 2–15 $m^3 ha^{-1}$ with low bias (0.7–4.2%). It seems that total forest biomass simulated by TRIPLEX1.0 is less accurate than tree volume with R^2 of 0.81 for temperate forest and 0.85 for boreal forest. The simulated mean errors and biases for total biomass are about 18–26 $t ha^{-1}$ and between 7 and 15%, respectively across 70 forest plots (Table 5). All *p* values were less than the critical value at $\alpha=0.05$.

Table 5

Summary statistics of comparing volume ($m^3 ha^{-1}$), and biomass ($t ha^{-1}$) between TRIPLEX1.0 simulations and field data observed from 70 plots in northeastern China's forest ecosystems (Zhu, 2005).

	Temperate forest		Boreal forest	
	Volume	Biomass	Volume	Biomass
<i>Regression</i>				
<i>n</i>	55	55	15	15
Slope	0.88	0.86	0.65	0.68
Se for slope	0.03	0.06	0.06	0.08
Intercept	27.55	17.51	76.75	29.24
Se for intercept	12.61	15.43	14.39	14.72
r^2	0.93	0.81	0.90	0.85
<i>F</i>	720.5	223.5	117.0	72.2
Degree of freedom	53	53	13	13
<i>Error and bias</i>				
Se for the simulation ^a	42.1	42.1	21.9	17.2
$\bar{\epsilon}^a$	14.6	18.4	1.6	26.1
Bias	4.2%	7.3%	0.7%	14.9%
<i>p</i>	<0.001	<0.001	<0.001	0.0006

^a Se, standard error of the predicted value for each observed value in the regression, which is a measure of the amount of error in the prediction for an individual observation; $\bar{\epsilon}$, average prediction error.

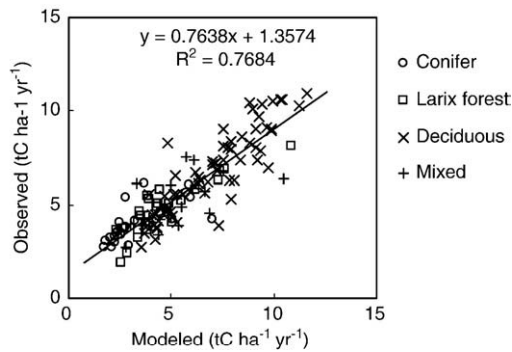


Fig. 7. Comparison of simulated forest NPP against 133 observed forest NPP in northeast China. The observed forest NPP data sets are obtained from the most comprehensive database with compiled by the Ph.D. dissertation of Luo (1996) and Ni et al. (2001). The database includes over 2000 measurements with about 690 forest stands and 17 major forest types across China.

NPP is a key ecosystem variable and an important component of forest carbon budgets. Since the NPP data for individual forest plot are not available for validating the TRIPLEX1.0 model, we have selected 133 observed NPP data sets from the most comprehensive national forest NPP database (Luo, 1996; Ni et al., 2001) for corresponding 4 main forest types located in the study area (Fig. 7). Overall, the agreement between model simulations and observations is reasonably good ($R^2 > 0.76$). The averaged NPP predicted by the model is close to the average NPP observation at ecosystem level, excepting for conifer boreal forest (Table 6). Unfortunately, we did not compare our model NPP simulation with NPP observations from 1990 to 1999, because the NPP observations for this period are not available.

In addition, averaged soil carbon predicted by model is compared with field measurements selected for the study region (Fig. 8). The results of comparison suggest that modeled values of soil carbon are within the range of independent measurements reported by Zhu (2005) and Yang and Li (2003) for conifer and *Larix*, and close to the measurements for deciduous and mixed forests.

These independent validations of TRIPLEX1.0 demonstrated that the model is able to simulate tree volume, NPP, total biomass and soil carbon for baseline conditions and provides us the confidence in applying the model for further investigating the potential impacts of future climate change on forest productivity and carbon budgets and extrapolating it to regional scale.

3.2. Impacts of future climate change and increasing CO₂ on NPP

The simulated NPP and NEP (net ecosystem productivity) for baseline [1999] are presented in Fig. 9a and b, respectively. Using this as baseline, the responses of NPP under different climate change

Table 6

Summary statistics of comparing NPP ($\text{t C ha}^{-1} \text{ yr}^{-1}$) between observed from 133 sites (Luo, 1996; Ni et al., 2001) and modeled using TRIPLEX1.0 for northeastern China's forest ecosystems.

	Conifer		<i>Larix</i> forest		Deciduous		Mixed	
	Observed	Modeled	Observed	Modeled	Observed	Modeled	Observed	Modeled
<i>n</i>	24		25		63		21	
R^2	0.51		0.69		0.77		0.51	
Max	3.1	3.3	4.1	5.4	5.5	5.8	3.8	3.8
Min	1.4	0.9	0.9	1.2	1.4	1.8	1.4	1.3
Average	2.0	1.7	2.3	2.3	3.4	3.5	2.5	2.4
Se for the simulation ^a		0.36		0.38		0.53		0.47
$\bar{\epsilon}^a$		0.31		0.04		-0.10		0.04
Bias		15.2%		1.5%		-2.8%		1.6%
<i>p</i>		<0.001		<0.001		<0.001		<0.001

^a Se, standard error of the predicted value for each observed value in the regression, which is a measure of the amount of error in the prediction for an individual observation; $\bar{\epsilon}$, average prediction error.

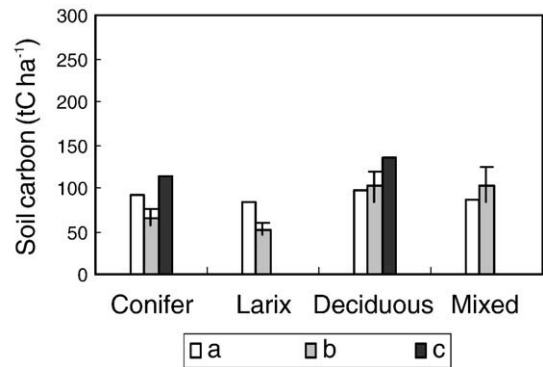


Fig. 8. Comparison between simulated and observed soil carbon for 4 major forest types. (a) refers to averaged values of model simulations in this study. (b) and (c) represent average values measured by Zhu (2005) and Yang and Li (2003), respectively. The vertical line represents standard error (SE) for b.

scenarios were calculated for whole study region. Experiment of climate change without CO₂ fertilization indicated relatively small response in NPP (Table 7; Fig. 10a). Simulated average NPP has increased from 38.6 Tg C yr^{-1} for baseline to 39.5 Tg C yr^{-1} with an average increase of 2.3% for the short term (2030s) and 42.6 Tg C yr^{-1} with an average of 10% for long term (2090s) under all three scenarios. The lowest increase of NPP is shown to be 6% for 2090s under the scenario B1 scenario and the highest increase of NPP is observed to be 14% under A2 scenario (Fig. 10a).

Increasing atmospheric CO₂ plus climate change scenario dramatically increased simulated NPP for most all 4 forest ecosystems in 21st century, especially in the region of boreal conifer forest (Table 7; Fig. 10). The combined effects of climate change and CO₂ fertilization on the increase of NPP were estimated to be 10–12% for 2030s and 28–37% in 2090s which are 4.9 times higher in 2030s and 3.2 times higher in 2090s than those simulations ignoring the effect of CO₂ fertilization under three scenarios, respectively (Fig. 10b; Table 7). The lowest NPP increases are observed under the scenario B1. This is consistent with the lower effects of moderate climate change on the carbon uptake in ecosystems. The spatial distribution of NPP increase (Figs. 12 and 13) exhibits a high spatial heterogeneity but shows a similar temporal pattern with a smaller magnitude. However, the results did not show significant difference of climate change impacts on NPP between three climate change scenarios for 21st century.

3.3. Impacts of future climate change and increasing CO₂ on carbon stocks

The average total biomass (above- and below-ground biomass) has consistently increased from 1.49 Pg C at baseline condition up to

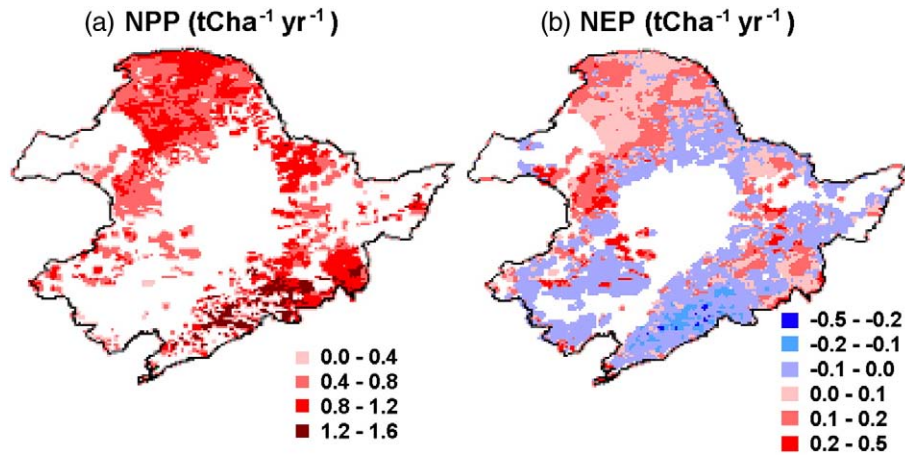


Fig. 9. Simulated spatial distribution of (a) NPP ($tC\ ha^{-1}\ yr^{-1}$) and (b) NEP ($tC\ ha^{-1}\ yr^{-1}$) for the baseline year of 1999.

1.75 Pg C for climate change without CO₂ fertilization and 1.92 Pg C under combined climate change and CO₂ fertilization over next 100 years (Table 7). The increase in percentage of total biomass is relatively higher for the three scenarios with CO₂ fertilized than those scenarios without CO₂ fertilization (also see Table 7). We observed some difference of biomass carbon accumulation under three different climate scenarios after 2070s (Fig. 11a and c), although there is no significant difference of biomass carbon accumulation ($\leq 1\%$) under different climate scenarios for the 2030s. However, the difference is observed to be larger (3%) for increase percentage of biomass carbon over the period of 2090s (Fig. 11a and c; Table 7), suggesting that the difference in three climate change scenarios (Fig. 3) would result in different biomass carbon accumulations in later 21st century.

As similar as the dynamics of biomass carbon, the simulated soil carbon stock (including litter and soil) does not show obvious difference among three climate change scenarios before 2060. However, in contrast to the climate change results, the dynamics of soil carbon stocks (Fig. 11b and d) differ remarkably from the biomass carbon accumulation as shown in Fig. 11a and c. The simulated results also indicated contrary temporal patterns of soil carbon under three climate scenarios for two different experiments. Results also suggest that the scenario A2 resulted in a lower soil carbon stock than do the

A1 and B1 at the end of 21st century, because of the higher increase in temperature and precipitation as shown in Fig. 3. A continuous decrease of soil carbon under all three scenarios was found for the climate change experiment without CO₂ fertilization. Fig. 11d shows that the soil carbon stock has been slightly decreased in early 30 years of the 21st century and followed by a steadily increases from 2040s to 2090s under climate change experiment with CO₂ fertilization. The reason is that the NPP enhanced by CO₂ fertilization has a positive effect on carbon stocks via a higher accumulation of biomass and litter. However, climate change has a negative effect on soil carbon stocks because more decomposition occurs while temperature and precipitation significantly increase in later 21st century. The simulated effects of CO₂ fertilization were to significantly offset the soil carbon loss due to climate change alone.

3.4. Impacts of future climate change and increasing CO₂ on carbon balance

Carbon balance is expressed by net ecosystem productivity (NEP) which is the difference between NPP and heterotrophic respiration. The simulated NEP for entire northeast China's forest ecosystems was estimated to be 4.25 Tg C yr⁻¹ for baseline condition (Table 7; Fig. 9b) and has increased by the 2090s under all three scenarios (Table 7) with

Table 7

Simulated effects of different climate change and increasing CO₂ scenarios on forest NPP, biomass and carbon balance of forest ecosystems in Northeast of China in 21st century. CGCM3.1 outputs for the period from 2001 to 2100, under three scenarios: (1) A1: Temperature and CO₂ increase 3 °C and 350–700 ppm; (2) A2: Temperature and CO₂ increase 4 °C and 350–850 ppm; and (3) B1, Temperature and CO₂ increase 2 °C and 350–550 ppm, respectively (also see Table 1).

Scenarios	Climate change without CO ₂ fertilization						Climate change with CO ₂ fertilization						1999 Baseline
	Total			Change (%)			Total			Change (%)			
	A1	A2	B1	A1	A2	B1	A1	A2	B1	A1	A2	B1	
NPP (TgC yr ⁻¹)													
2030s	39.6	39.8	39.0	3	3	1	43.2	43.4	42.4	12	12	10	38.6
2090s	42.6	44.0	41.1	10	14	6	51.0	52.8	49.3	32	37	28	
NEP (TgC yr ⁻¹)													
2030s	0.31	0.22	0.23	–	–	–	3.83	3.76	3.69	–	–	–	4.25
2090s	0.32	–2.72	0.91	–	–	–	8.81	6.06	9.11	–	–	–	
Biomass (PgC)													
2030s	1.65	1.66	1.64	11	11	10	1.69	1.70	1.68	14	14	13	1.49
2090s	1.75	1.77	1.73	18	19	16	1.92	1.94	1.89	29	30	27	
Soil C stock (PgC)													
2030s	6.06	6.06	6.06	5	5	5	6.13	6.13	6.12	35	35	35	4.52
2090s	6.08	6.03	6.08	3	3	3	6.51	6.47	6.51	44	44	44	
Ecosystem C stock (PgC)													
2030s	7.71	7.72	7.70	28	28	28	7.82	7.83	7.80	30	30	30	6.01
2090s	7.83	7.80	7.81	30	30	30	8.43	8.41	8.40	40	40	40	

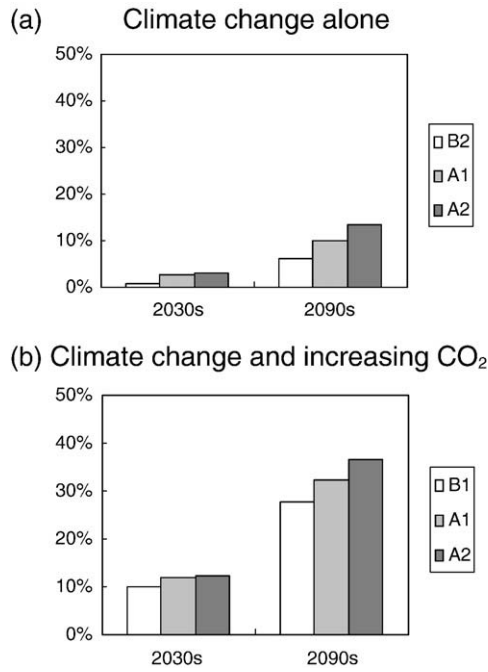


Fig. 10. Relative changes of NPP in 2030s (averaged over 2030–2040) and 2090s (averaged over 2090–2100) under different three scenarios (A1, A2, B1) compared with baseline (1999). (a) refers to experiments of climate change alone; (b) (a) refers to climate change with CO₂ fertilization, respectively.

CO₂ fertilization, but decreased in the case without CO₂ fertilization. However, only the scenario A2 without CO₂ fertilization caused the forest ecosystems of northeast China as a carbon source in the 2090s (Table 7). The spatial distribution of NEP for the climate change alone without CO₂ fertilization scenario (Fig. 12d,e,f) and the climate change with CO₂ fertilization scenario (Fig. 13d,e,f) illustrated that NEP of boreal conifer forests (located at the north of the study region) are more sensitive to climate change and CO₂ fertilizing in 21st century. Our results also suggested that most forested area in northeast China will be a carbon sink in the 2090s for the scenarios A1 and B1, excepting scenarios A2 without CO₂ fertilization, which assumes a highest carbon emission rate among the three climate scenarios.

4. Discussions

4.1. Uncertainty and limitations of the model

TRIPLEX1.0 simulates forested land without human-induced changes such as agriculture, forest harvest, grazing and urbanization, which can further complicate the systems by enhancing changes to the terrestrial ecosystems (Chapin et al., 2004). In this study, we have focused on the forested lands where the TRIPLEX1.0 has been intensively tested with various field measurements in Canadian boreal forests (Peng et al., 2002; Zhou et al., 2004, 2005a,b). The results presented here represent our first testing of TRIPLEX1.0 model for boreal and temperate forests in northeastern China. The model validation with independent observations suggests that TRIPLEX1.0 is able to estimate the forest NPP, total biomass and soil carbon under baseline conditions. Unfortunately, the existing formulation of TRIPLEX1.0 has no fire disturbance submodel and is unable to explicitly predict the impacts of fire disturbances on forest NPP and carbon budgets (see discussion below). The absence of a shrub module and a moss and lichen layer at the soil surface in boreal forest is additional weakness of the model, because both shrub and moss may account for significant proportion of NPP and biomass carbon. Moreover, we did not take into accounting the potential impacts of land use change and forest harvesting on forest NPP and carbon fluxes, because the current version of TRIPLEX1.0 model does not have, unfortunately, the forest harvesting or land-use module. The integration of forest harvesting module into TRIPLEX1.0 model is planned for the ongoing research efforts in next step. These limitations of the model may cause potential uncertainty in modeling the NPP, biomass and soil carbon stocks under the baseline conditions and represent the expected variations when comparing with field measurements (Tables 5 and 6).

One of the weaknesses is the lack of trees and their response to increasingly stressful climate (Meehl and Tebaldi, 2004), and increase in stomata (in water use) with increases in CO₂, documented in full-glacial needles and pre-CO₂ increase herbarium specimens (Beerling and Woodward, 2003). The potential for carbon saturation over this century and for reductions in growth because of heat and drought stress are critical uncertainties (Schär et al., 2004; Meehl and Tebaldi, 2004). The extreme events such as the 2003 European heat wave and drought having the potential to significantly alter long-term forest productivity and carbon balances, and may counteract the effects of

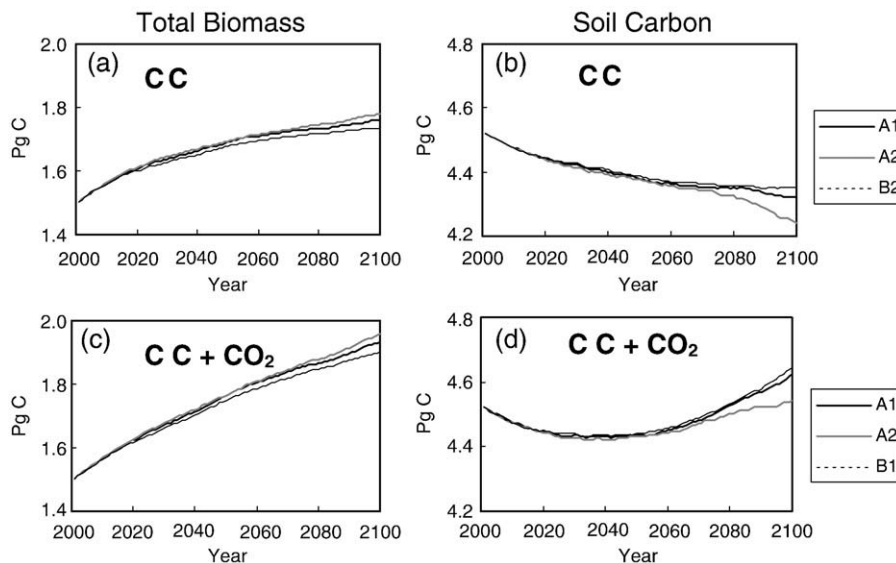


Fig. 11. Simulated temporal dynamics of total biomass (left) (Pg C = 10¹⁵ g C) and soil carbon stock (right) (Pg C) under 3 different climate change scenarios with two experiments: (1) climate change alone (CC) and (2) climate change with CO₂ fertilization (CC + CO₂).

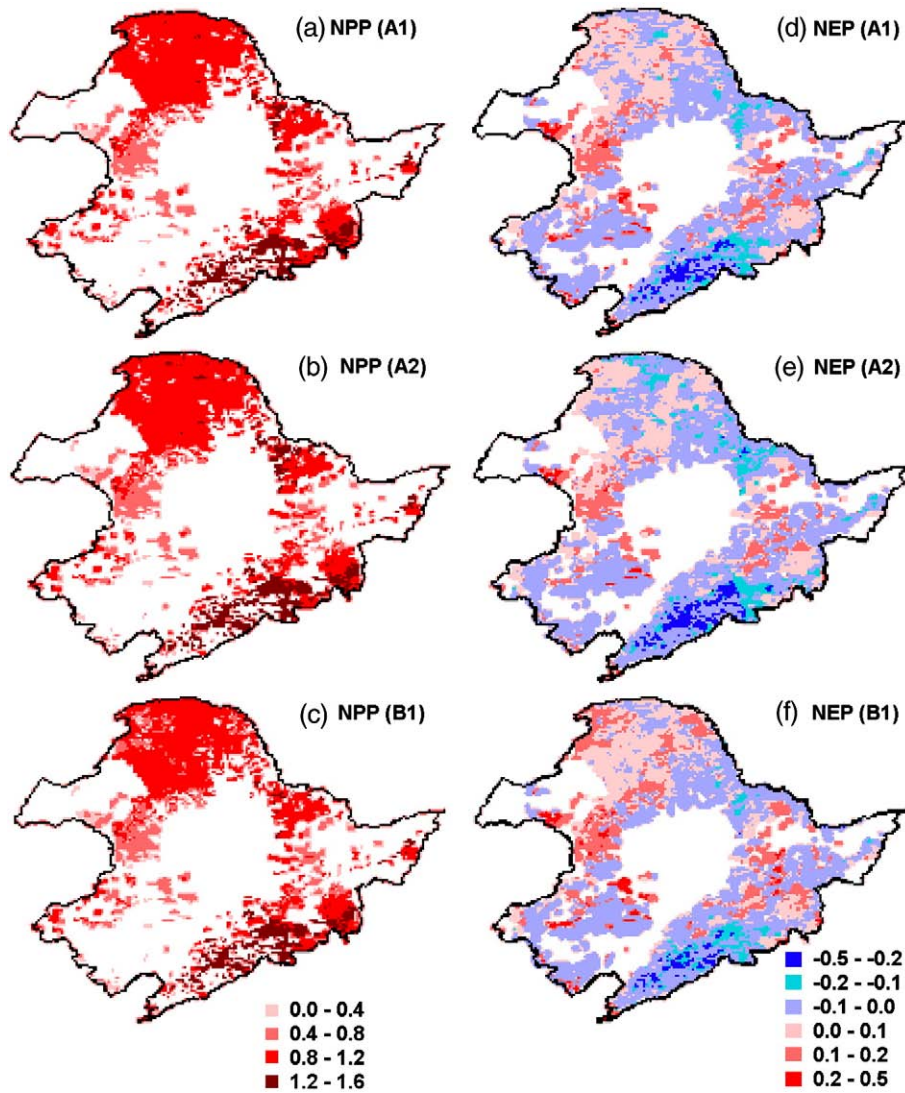


Fig. 12. The spatial distributions of simulated NPP ($\text{t C ha}^{-1} \text{ yr}^{-1}$) under the climate change scenarios (without CO_2 fertilization effect) of A1 (a), A2 (b) and B1 (c), respectively and simulated NEP ($\text{t C ha}^{-1} \text{ yr}^{-1}$) under scenarios of A1 (d) A2 (e), and B1 (f), respectively for 2090s.

the anticipated mean warming and lengthening of the growing season, and reduce the productivity of ecosystems, reversing sinks to sources. The increasing climate stress (e.g. more intense, more frequent, and longer lasting heat waves and droughts) seems likely to increasingly reduce NPP and carbon sequestration over the next century (Meehl and Tebaldi, 2004; Ciais et al., 2005). In addition, the TRIPLEX1.0 has not considered the phytotoxic effects of simultaneous exposure to elevated tropospheric O_3 , which is increasing globally (Fowler et al., 1999; IPCC, 2001), but, less well recognized, and is probably reducing the potential enhancement of forest NPP and carbon storage by elevated CO_2 (Felzer et al., 2004; Karnosky et al., 2005). Future study to address the uncertainty due to the effects of climate stress stomata conductance, and exposure ozone on forest carbon dynamics will certainly improve our understanding of impacts of climate change on forest ecosystem structure and function in China.

4.1.1. Fire disturbance

Fire disturbance regimes, as an important control on ecosystem processes in global boreal forests, are highly sensitive to possible future climate change because fire behavior is affected by fuel moisture – a variable that is related to precipitation, relative humidity, air temperature and wind speed (Weber and Flannigan, 1997; Harden et al., 2000). Fire disturbance is recognized as an important factor in

NPP and carbon emission (Cahoon et al., 1994; Harden et al., 2000; Wang et al., 2001). As it can alter the natural species composition of an ecosystem, fire disturbance is an important determinant of forest ecosystem dynamics (determining the distribution of stand ages) and changes decomposition rates, organic layer thickness and other ecosystem properties. These influences on NPP and carbon dynamic processes all depend both on the state of the forest ecosystem and the fire regime itself (e.g. fire severity and return interval). In boreal forests, 10 to 30% of annual NPP may have been consumed globally by fire over the past 6500 years (Harden et al., 2000). However, the response of soil C and respiration to fire is highly variable within boreal forest ecosystems. Forest fires have burned about 5.6×10^6 ha of forested and non-forested lands in Heilongjiang Province between 1966 and 1987 but the 1987 wildfire burned about 1.14×10^6 ha of boreal forests in northeast of China (Di and Ende, 1990; Cahoon et al., 1994; Goldammer and Stocks, 2000). Wang et al. (2001) quantified the influence of fire on carbon emission and net primary production of boreal forests in this region and found the total larch forest (*Larix gmelinii*) ecosystem contained a large amounts of carbon (123.8 – $251.4 \text{ t C ha}^{-1}$) and the 1987 conflagration resulted in a net carbon emission of 2.5×10^7 – $4.9 \times 10^7 \text{ t C}$ to the atmosphere. However, the effects of fire on forest NPP and carbon dynamics are poorly understood due to the lack of detailed study in this region (Harden

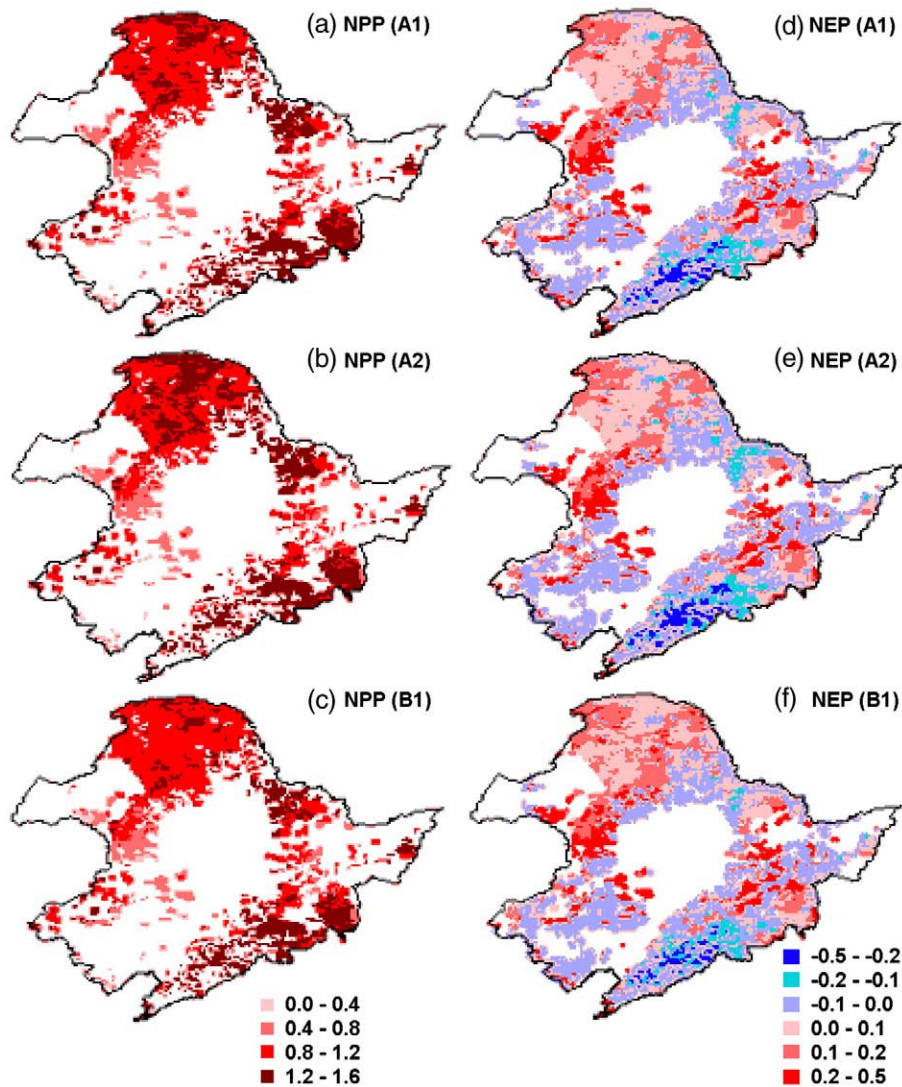


Fig. 13. The spatial distributions of simulated NPP ($\text{t C ha}^{-1} \text{yr}^{-1}$) under the climate change scenarios (with CO_2 fertilization effects) of A1 (a), A2 (b) and B1 (c), respectively and simulated NEP ($\text{t C ha}^{-1} \text{yr}^{-1}$) under scenarios of A1 (d) A2 (e), and B1 (f), respectively for 2090s.

et al., 2000). Many of these factors have not been explicitly accounted for in the simulations reported here and need further study, especially in connection with the changes in NPP and carbon balance associated with climate change as well as insect infestations of needle-leaved trees in this region, which might act as significant carbon source under realistic condition of pest enhancement (Kurz et al., 2008).

4.2. Response of forest NPP and carbon budgets to climate change and increasing CO_2

Generally speaking, productivity of terrestrial ecosystems is clearly very sensitive to climate perturbations. It is well-known that temperature and precipitation are dominant controls on plant photosynthesis (Lieth, 1975; Dai and Fung, 1993). Climate change will affect NPP in a number of different ways (Houghton and Woodwell, 1989; IPCC, 2001). Elevated temperatures may increase NPP through metabolically enhanced photosynthesis as well as by increasing nutrient availability through higher rates of decomposition. Elevated temperatures, however, may also decrease NPP by decreasing soil moisture and enhancing plant respiration. A dominant feature of climate change predicted by GCMs for a doubling of atmospheric CO_2 is a significant increase in annual air temperature – the CGCM3.1 used in the present study projects changes of between 1.5 and 4 °C for northeastern China. As

productivity in northern boreal forest ecosystems is substantially limited by low temperature (Lieth, 1975) and N availability (Vitousek and Howarth, 1991), NPP increases under climate change and increasing CO_2 will likely be largely influenced by the effectiveness of elevated temperatures in enhancing N availability. As reported by Piao et al. (2003, 2005), climate warming greatly enhanced plant growth for the cold and humid regions in China, and resulted in a significant increase in greenness and sequentially forest carbon stock in northeast of China.

There has been much debate about the possible effects of increased atmospheric CO_2 concentrations on NPP and carbon sequestration (Mooney et al., 1991; Bazzaz and Fajer, 1992; Norby et al., 1992; Oechel et al., 1994; King et al., 1995). There also remain large uncertainties in attempts to model the direct effects of CO_2 fertilization on plant growth (Goudriaan, 1992; Polglase and Wang, 1992; Luo and Mooney, 1999; IPCC, 2001; Norby et al., 2005; Körner et al., 2005; Matthews, 2007). It has been suggested that growth stimulation of natural biomes by elevated CO_2 levels in the atmosphere and by enhanced N deposition from the atmosphere has contributed to the missing C sink (Keeling et al., 1989; Taylor and Lloyd, 1992; Harrison et al., 1993; Hudson et al., 1994; Schimel et al., 2001). While the CO_2 fertilization hypothesis provides one possible explanation for the missing anthropogenic C sink, this conclusion is far from conclusive. Much controlled research on the direct effects of CO_2 has been carried out on

leaves and individual plants but whole-plant respiration, tissue allocation and nutrient dynamics of intact ecosystems and large-scale biomes are still poorly understood. Scaling up measurements from leaves and individuals to stands and ecosystems may introduce significant error; this has led to unresolved concerns that elevated CO₂ may not affect stands in the same way that single individuals are affected (Körner and Bazzaz, 1996). There is a clear need for further empirical studies (Ceulemans and Mousseau, 1994; Norby et al., 2005; Körner et al., 2005). Mainstream literature contains no measurement of growth response by mature trees that have been fumigated with CO₂ from their germination (Tognetti et al., 2000).

The results of NNP enhancement simulated by TRIPLEX1.0 presented here are consistent with the recent FACE experiments (Norby et al., 2005), global analysis of Melillo et al. (1993) and Matthews (2007), and site-specific investigation of Peng and Apps (1998, 1999) in Canadian boreal forest ecosystems. With no CO₂ fertilization effect included in the simulations, the results of Melillo et al. indicated a small increase (about 4.5%) in mean NPP for the global boreal forest under a doubled CO₂ climate change scenario. When the CO₂ fertilization effect was included, higher responses by as much as 35% were found for the boreal forest biome. Recently, Norby et al. (2005) have analyzed the response of NPP to elevated CO₂ (about 550 ppm) in four free-air CO₂ enrichment experiments in temperate forests in North America and Europe and show that the response of forest NPP to elevated CO₂ is about 21–25% and highly conserved across a broad range of productivity. Using a coupled climate-carbon model to explore the effects of carbon fertilization on future climate, Matthews (2007) also found that carbon fertilization will be the leading contributor to carbon uptake by terrestrial sinks over the next century. The results suggested that the 5-year averaged NPP increase in enhanced-CO₂ run for the FACE study (Norby et al., 2005) was about 25%, which is close to the Norby and colleagues estimate and TRIPLEX1.0 model simulation in this study. The study highlights the critical role of carbon dioxide fertilization in influencing future climate change, and emphasizes the need for a better understanding of its role in carbon cycling and climate feedbacks. Another recent observations of older and larger deciduous trees in a mature Swiss forest (Körner et al., 2005) demonstrated that physiological responses (e.g., photosynthesis, foliar N and nonstructural carbohydrate concentrations) were similar to those of younger trees in temperate zone, suggesting that the effect of CO₂ fertilization on forest NPP is now firmly established. However, recent model-based estimate of global carbon budget by Canadell et al. (2007) indicated that a lowered uptake rather than increasing uptake of CO₂ globally between 2000–2006. The reason is still unknown.

4.3. Impacts of climate change on forest structure and succession

The changes in atmospheric CO₂ concentration, temperature and precipitation regimes will likely affect the structure and distribution of boreal and temperate forests in northeast of China through their influences on forest regeneration, growth, mortality, physiological processes (e.g., photosynthesis, respiration) and ecological processes (e.g., the decomposition of soil organic materials). Such changes will result in a northward shift in the natural range of various forest types and species in this region. Quantifying the response of forest ecosystems to future climate change is vital, both nationally and regionally. In the earlier modeling studies, on one hand, Zhang and Yang (1993) used the Hodridge life-zone scheme for investigating the climate-vegetation relationship and interaction for Chinese vegetation. Hulme et al. (1992) simulated the distributions of 9 vegetation types under both current climate and future climate change scenarios projected by GCM. However, both studies are limited by using the empirical statistical approaches and coarse spatial resolution, and did not capture the vegetation dynamics under a changing environment (Peng, 2000). On the other hand, Ni et al. (2000) adopted the terrestrial biosphere model of BIOME3 to predict the response of Chinese vegetation to future climate change scenarios for 2070–2099 projected by Hadley Centre coupled ocean-atmosphere GCM

(Mitchell et al., 1995; Johns et al., 1997). They found that a doubled CO₂ climate shifts biomes north and west and climate change alone yielded a large reduction in boreal deciduous forest and a decline in desert, alpine tundra. However, this study was limited not only by equilibrium simulation of potential vegetation types but also by ignoring the possible vegetation succession and migration under a changing climate and associated fire disturbances. The Dynamic Global Vegetation Models (DGVMs) [e.g. IBIS, Foley et al., 1996; Sheffield DGVM, Woodward and Beerling, 1997; LPJ DGVM, Sitch et al., 2003; TCEM, Arora and Boer, 2005] seem to be able to overcome some of these limitations and provide better understanding of the impacts of future climate change and fire disturbance on vegetation dynamics (Peng, 2000). Unfortunately, in this study, the current version of TRIPLEX1.0 is limited for modeling vegetation succession and future dynamics. Incorporating a dynamic vegetation module into the TRIPLEX1.0 will be one of high priorities and remain a big challenge for the new version of TRIPLEX model.

5. Conclusions

The response of the terrestrial ecosystems to increasing atmospheric carbon dioxide and global warming is key uncertainty in current projections of future carbon sinks and climate change. The results presented here show that the simulated forest yield, NPP, total biomass and soil carbon are consistent with observed data across northeast of China, suggesting that the improved TRIPLEX1.0 model is able to simulate forest growth and carbon dynamics of boreal and temperate forest ecosystems at regional scale. The climate change would increase forest NPP and carbon in biomass but decrease overall soil carbon under all three climate change scenarios. Combined effects of climate change and increased atmospheric CO₂ would result in increased NPP and carbon in vegetation and soil for both short-term (30–40 years) and long-term (90–100 years). The results of the effects of CO₂ fertilization on NPP simulated by TRIPLEX1.0 are consistent with the recent FACE experiments in temperate forests in North America and Europe (Norby et al., 2005), global analysis of Melillo et al. (1993) and Matthews (2007), and site-specific investigation in Canadian boreal forest ecosystems (Peng and Apps, 1998, 1999). The simulated effects of CO₂ fertilization were to offset the soil carbon loss due to climate change alone. Overall, the forest ecosystems of northeastern China are very sensitive to changes in future climate change and increasing CO₂ in the atmosphere. However, these simulations do not consider likely the effects of tropospheric ozone, changes in forest structure and succession, fire disturbance and insect infestation, which inevitably introduce some uncertainty in model simulations. Future study regarding these issue and model improvement will certainly improve our understanding of the potential impacts of climate change on Chinese northern forest ecosystems in 21st century.

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References

- Alemdag, I.S. 1984. Wood Density Variation of 28 Trees Species from Ontario. Canadian Forestry Service, Petawawa National Forestry Institute. Information Report PI-X-45, 11 pp.
- Arora, V., Boer, G., 2005. A parameterization of leaf phenology for the terrestrial ecosystem component of climate models. *Glob. Chang. Biol.* 11, 39–59.

- Bazzaz, F.A., 1990. The response of natural ecosystems to the rising global CO₂ levels. *Ann. Rev. Ecol. Syst.* 21, 167–196.
- Bazzaz, F.A., Fajer, E.D., 1992. Plant life in a CO₂-rich world. *Sci. Am.* 266, 68–74.
- Beerling, D.J., Woodward, F.I., 2003. Ecophysiological responses of plants to global environmental change since the Last Glacial Maximum. *New Phytol.* 125 (3), 641–648.
- Bossel, H., 1996. TREEDYN3 forest simulation model. *Ecol. Model.* 90, 187–227.
- Bousquet, P., Ciais, P., Peylin, P., Ramonet, M., Monfray, P., 1999. Inverse modeling of annual atmospheric CO₂ sources and sinks I. Method and control inversion. *J. Geophys. Res.* 104 (D21), 26161–26178.
- Canadell, J.G., Queré, C.L., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, Nathan, P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks. *PNAS* 104, 1886–18870.
- Ceulemans, R., Mousseau, M., 1994. Effects of elevated atmospheric CO₂ on woody plants. *New Phytol.* 127, 425–446.
- Cahoon, D.R., Stocks, B.J., Levine, J.S., Cofer, W.R., Pierson, J.M., 1994. Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia. *J. Geophys. Res.* 99 (D9), 18627–18638.
- Cao, M.K., Woodward, F.I., 1998. Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. *Nature* 393, 249–252.
- Cao, M.K., Price, S., Li, K.R., Tao, B., Small, J., Shao, X., 2003. Response of terrestrial carbon uptake to climate interannual variability in China. *Glob. Chang. Biol.* 9, 536–546.
- Chapin, F.S., Callaghan, T.V., Bergeron, Y., Fukuda, M., Johnstone, J.F., Juday, G., Zinov, S.A., 2004. Global change and the boreal forest: thresholds, shifting states or gradual change? *Ambio* 33, 361–365.
- Chen, X., 2002. Modeling the effects of global climatic change at the ecotone of boreal larch forest and temperate forest in northeast China. *Clim. Change* 55, 77–97.
- Cheng, W., Sims, D.A., Luo, Q., Coleman, J.S., Johnson, D.W., 2000. Photosynthesis, respiration, and net primary production of sunflower stands in ambient and elevated atmospheric CO₂ concentrations: an invariant NPP:GPP ratio? *Glob. Chang. Biol.* 6, 931–941.
- Choi, S.D., Lee, K., Chang, Y.S., 2002. Large rate of uptake of atmospheric carbon dioxide by planted forest biomass in Korea. *Glob. Biogeochem. Cycles* 16 (4), 1089. doi:10.1029/2002GB001914.
- Ciais, P., Tans, P.P., Trolier, M., White, J.W.C., Francey, R.J., 1995. A large Northern-hemisphere terrestrial CO₂ sink indicated by the C-13/C-12 ratio of atmospheric CO₂. *Science* 269, 1098–1102.
- Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* 437, 529–533.
- Coops, N.C., Waring, R.H., Brown, S.R., Running, S.W., 2001. Comparisons of predictions of net primary production and seasonal patterns in water use derived with two forest growth models in southwestern Oregon. *Ecol. Model.* 142, 61–81.
- Cramer, W., Bondeau, A., Woodward, F.I., Prentice, I.C., Betts, R.A., Brovkin, V., Cox, P.M., Fisher, V., Foley, J.A., Friend, A.D., 2001. Global response of terrestrial ecosystem structure and function to CO₂ and climate change: results from six dynamic global vegetation models. *Glob. Chang. Biol.* 7, 357–373.
- Deng, D., Chen, J.M., Plummer, S., Chen, M., Pisek, J., 2006. Global LAI algorithm integrating the bidirectional information, *IEEE T. Geosci. Remote. Sens.* 44, 2219–2229.
- Dewar, R.C., Cannell, M.G.C., 1992. Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. *Tree Physiol.* 11, 49–71.
- Dewar, R.C., Medlyn, B.E., McMurtie, R.E., 1999. Acclimation of the respiration/photosynthesis ratio to temperature: insights from a model. *Glob. Chang. Biol.* 5, 615–622.
- Dai, A., Fung, I.Y., 1993. Can climate variability contribute to the 'missing' CO₂ sink? *Glob. Biogeochem. Cycles* 7, 599–609.
- Di, X., Ende, J., 1990. The forest congregation of May, 1987 in northeast China. In: Goldammer, J.G., Jenkins, M.J. (Eds.), *Fire in Ecosystems of Boreal Eurasia*. SPB Academic Publishers, The Hague, pp. 169–174.
- Dixon, R.K., Schroeder, P.E., and Winjum, J.K. (1991), Assessment of promising forest management practices and technologies for enhancing the conservation and sequestration of atmospheric carbon and their costs at the site level. U.S. Environ. Prot. Agency Res. Dev. EPA, 600, 3–91, 67, 138pp.
- Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Houghton, R.A., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. *Science* 263, 185–190.
- Fan, S., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J., Takahashi, T., Tans, P., 1998. A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science* 282, 442–446.
- Fang, J.Y., Chen, A.P., 2001. Dynamic forest biomass carbon pools in China and their significance. *Acta Bot. Sin.* 43, 967–973.
- Fang, J.Y., Liu, G.H., Xu, S.L., 1996. Soil carbon pool in China and its global significance. *J. Environ. Sci.* 8, 249–254.
- Fang, J.Y., Wang, G.G., H Liu, G., Xu, S.L., 1998. Forest biomass of China: an estimate based on the biomass–volume relationship. *Ecol. Appl.* 8, 1084–1091.
- Fang, J.Y., Chen, A.P., Peng, C.H., Zhao, S.Q., C. Li, J., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* 292, 2320–2322.
- Fang, J.Y., Piao, S.L., Field, C., Pan, Y., Guo, Q., Zhou, L., Peng, C.H., Tao, S., 2003. Increasing net primary production in China from 1982 to 1999. *Front. Ecol. Environ.* 1, 293–297.
- Fang, J.Y., Oikawa, T., Kato, W.M., Wang, Z., 2005. Biomass carbon accumulation by Japan's forests from 1947 to 1995. *Global Biogeochem. Cycles* 19 (GB2004). doi:10.1029/2004GB002253.
- Feng, Z.W., Wang, X.K., Wu, G., 1999. Biomass and NPP of Chinese forest ecosystems. Science Press, Beijing.
- Felzer, B., Kicklighter, D., Mellilo, J., Wang, C., Zhuang, Q., Prinn, R., 2004. Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. *Tellus* 56B, 230–248.
- FRIC, 1999. Forest Resources Inventory of China. Chinese Ministry of Forestry, Beijing, China, 125 pp. (in Chinese).
- Friedlingstein, P., Funf, I., Holland, E., John, J., Brasseur, G., Erickson, D., Schimel, D., 1995. On the contribution of CO₂ fertilization to the missing biospheric sink. *Glob. Biogeochem. Cycles* 9, 541–556.
- Foley, J.A., Prentice, I.C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., Haxeltine, A., 1996. An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *Glob. Biogeochem. Cycles* 10, 603–628.
- Fowler, D., Cape, J.N., Coyle, M., Flechard, C., Kuylenstierna, J., Hicks, K., Derwent, D., Johnson, C., Stevenson, D., 1999. The global exposure of forests to air pollutants. *Water Air Soil Pollut.* 116, 5–32.
- Gao, Q., Zhang, X., 1997. A simulation study of responses of the northeast China transect to elevated CO₂ and climate change. *Ecol. Appl.* 7, 470–483.
- Gao, Q., Yu, M., Yang, X.S., 2000. An analysis of sensitivity of terrestrial ecosystem in China to climate change using spatial simulation. *Clim. Change* 47, 373–400.
- GCP, 2004. Global Carbon Project. (<http://www.globalcarbonproject.org/>).
- Gifford, R.M., 1995. Whole plant respiration and photosynthesis of wheat under increased CO₂ concentration and temperature: long-term vs. short-term distinctions for modelling. *Glob. Chang. Biol.* 1, 385–396.
- Goldammer, J.G., Stocks, B.J., 2000. Eurasian perspective of fire: dimension, management, policies, and scientific requirements. In: Canadell, J.G., Dickinson, R., Hibbard, K., Raupach, M., Young, O. (Eds.), *Fire, Climate Change, and Carbon Cycling in the GCP*. 2003. Global Carbon Project: Science framework and implementation, Earth System Science Partnership Report No. 1; GCP Report No. 1. 69 pp. Academic press, Canberra.
- Gifford, R.M., 1979. Carbon dioxide and plant growth under water and light stress: implication for balancing the global carbon budget. *Search* 10, 316–318.
- Goodale, C.L., Apps, M.J., Birdsey, R.A., Richard, A., Field, C.B., Heath, L.S., Houghton, R.A., Jenkins, J.C., Kohlmaier, G.H., Kurz, W., et al., 2002. Forest carbon sinks in the Northern Hemisphere. *Ecol. Appl.* 12, 891–899.
- Goudriaan, J., 1992. Biosphere structure, carbon sequestering potential and the atmospheric 14C carbon record. *J. Exp. Bot.* 43, 1111–1119.
- Goulden, M.L., Wofsy, S.C., Harden, J.W., Trumbore, S.E., Crill, P.M., Gower, S.T., Fries, T., Daube, B.C., Fan, S.M., Sutton, D.J., 1998. Sensitivity of boreal forest carbon balance to soil thaw. *Science* 279, 214–217.
- Gower, S.T., Vogel, J.G., Norman, J.M., Kucharik, C.J., Steele, S., Stow, T.K., 1997. C distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. *J. Geophys. Res.* 102 (D24), 29029–29041.
- Harden, J.W., Trumbore, S.E., Stocks, B.J., Hirsch, A., Gower, S.T., O'Neill, K.P., Kasichke, E.S., 2000. The role of fire in the boreal carbon budget. *Glob. Chang. Biol.* 6 (Suppl. 1), 174–184.
- Harrison, K., Broecker, W., Bonani, G., 1993. A strategy for estimating the impact of CO₂ fertilization on soil carbon storage. *Glob. Biogeochem. Cycles* 7, 69–80.
- Houghton, R.A., 2003. Why are estimates of the terrestrial carbon balance so different? *Glob. Chang. Biol.* 9, 500–509.
- Houghton, R.A., Woodwell, G.M., 1989. Global climatic change. *Sci. Am.* 260, 36–44.
- Hudson, R.J.M., Gherini, S.A., Goldstein, R.A., 1994. Modeling the global carbon cycle: nitrogen fertilization of the terrestrial biosphere and the 'missing' CO₂ sink. *Glob. Biogeochem. Cycles* 8, 307–333.
- Hulme, M., Wigley, T., Jiang, T., 1992. Climate change due to the greenhouse effect and its implications for China. WWF Report, Gland.
- IPCC, 2001. Climate Change 2001: The Scientific Basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Cambridge University Press, pp. 185–237.
- IPCC, 2005. IPCC Model Output. CCCMA CGCM3.1 (74) data (NetCDF files). Available from <https://esg.lln.gov:8443/index.jsp>.
- IGCAS (Institute of Geography, Chinese Academy of Sciences), 1996. Digitized vegetation map of China. National Laboratory for GIS and Remote Sensing, Beijing.
- ISSCAS (Institute of Soil Science, Chinese Academy of Sciences), 1986. The soil atlas of China. Cartographic Publishing House, Beijing.
- Jackson, R.B., Schlesinger, W.H., 2004. Curbing the US carbon deficit. *PNAS* 101, 15827–15829.
- Jiang, H., Apps, M.J., Zhang, Y.L., Peng, C.H., Woodard, P., 1999. Modeling the spatial pattern of net primary productivity in Chinese forest. *Ecol. Model.* 122, 225–238.
- Johns, T.C., Carnell, R.E., Crossley, J.F., Gregory, J.M., Mitchell, J.F.B., Senior, C.A., Tett, S.F.B., Wood, R.A., 1997. The second Hadley Centre coupled ocean-atmosphere GCM: model description, spin-up and validation. *Clim. Dyn.* 13, 103–134.
- Karnoski, D.F., Pregitzer, K.S., Zak, D.R., Kubeske, M.E., Hendrey, G.R., Weinstein, D., Nosal, M., Percy, K.E., 2005. Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell Environ.* 28, 965–981.
- Kauppi, P.E., Mielikainen, K., Kuusela, K., 1992. Biomass and carbon budget of European forests, 1971 to 1990. *Science* 256, 70–74.
- Kimball, B.A., 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agron. J.* 75, 779–788.
- Keeling, C., Bacastow, R.S., Carter, A.F., Piper, A.F., Whorf, S.C., Heimann, T.P., Mook, M., Roeloffzen, W.G., 1989. A three-dimension model of atmospheric CO₂ transport based on observed winds, I. Analysis of observation data. In: Peterson, D.H. (Ed.), *Aspects of Climate Variability in the Pacific and Western Americas*. Geophys. Monogr. Ser., vol. 55. AGU, Washington, DC, pp. 165–236.
- Kimball, J.S., Thornton, P.E., White, M.A., Running, S.W., 1997. Simulating forest productivity and surface-atmosphere carbon exchange in the BOREAS study region. *Tree Physiol.* 17, 589–599.

- King, A.W., Emanuel, W.R., Wullschlegler, S.D., Post, W.N., 1995. In search of the missing carbon sink: a model of terrestrial biospheric response to land-use change and atmospheric CO₂. *Tellus* 47B, 501–519.
- Korner, C., Bazzaz, F.A., 1996. Carbon Dioxide, Populations and Communities. Academic Press, San Diego, CA. 465 pp.
- Körner, C., Asshoff, R., Bignucolo, O., Hättenschwiler, S., Keel, S.G., Peláez-Riedl, S., Pepin, S., Siegwolf, R.T.W., Zotz, G., 2005. Carbon flux and growth in mature deciduous forest trees exposed to elevated CO₂. *Science* 309, 1360–1362.
- Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., Safranyik, L., 2008. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452, 987–990.
- Landsberg, J.J., Waring, R.H., 1997. A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Ecol. Model.* 95, 209–228.
- Li, X., 1995. Modelling the response of vegetation in Northeast China transect to global change. *J. Biogeogr.* 22, 515–522.
- Li, K.R., Wang, S.Q., Cao, M.K., 2004. Vegetation and soil carbon storage in China. *Sci. China, Ser D* 47, 49–57.
- Lieth, H., 1975. Modeling the primary production of the world. In: Lieth, H., Whittaker, R.H. (Eds.), *Primary Productivity of the Biosphere*. Springer-Verlag, New York, pp. 7–263.
- Liu, J., Peng, C.H., Dang, Q., Apps, M.J., Jiang, H., 2002. A component objective model strategy for reusing ecosystem models. *Comput. Electron. Agric.* 35, 17–33.
- Luo, T.X., 1996. Patterns of biological production and its mathematical models for main forest types of China, Ph.D. Dissertation, Committee of Synthesis Investigation of Natural Resources, Chinese Academy of Sciences, Beijing, 211 pp.
- Luo, Y.Q., Mooney, H.A., 1999. Carbon Dioxide and Environmental Stress. Academic Press, San Diego, CA. p. 413.
- Matthews, H.D., 2007. Implications of CO₂ fertilization for future climate change in a coupled climate-carbon model. *Glob. Chang. Biol.* 13, 1–11. doi:10.1111/j.1365-2486.2007.01343.x
- Metherell, A.K., Harding, L.A., Cole, C.V., and Parton, W.J., 1993. CENTURY Soil Organic Matter Model Environment Technical Documentation Agroecosystem Version 4.0. GPSR Technical Report No. 4, United States Department of Agriculture, Agricultural Research Service, Great Plains Systems Research Unit. URL <http://www.nrel.colostate.edu/projects/century/> [cited 10 May 2004].
- Mitchell, J.F.B., Johns, T.C., Gregory, J.M., Tett, S.F.B., 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature* 376, 501–504.
- Meehl, G.A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305, 994–997.
- Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore, B., Vorosmarty, C.J., Schloss, A.L., 1993. Global climate change and terrestrial net primary production. *Nature* 363, 234–240.
- Mooney, H.A., Drake, B.G., Luxmoore, R.L., Oechel, W.C., Pitelka, L.F., 1991. Predicting ecosystem response to elevated CO₂ concentrations. *bioScience* 41, 96–104.
- Morrison, J.L., Gifford, R.M., 1984. Plant growth and water use with limited water supply in high CO₂ concentrations. I. Leaf Area, water use and transpiration. *Aust. J. Plant Physiol.* 11, 361–374.
- Nabuurs, G.J., Mohren, G.M.J., 1995. Modelling analysis of potential carbon sequestration in selected forest types. *Can. J. For. Res.* 25, 1157–1172.
- National Soil Survey Office (NSSO), 1995a. Soil Species of China, vol. 4. China Agriculture Press, Beijing (in Chinese).
- National Soil Survey Office (NSSO), 1995b. Soil Species of China, vol. 5. China Agriculture Press, Beijing (in Chinese).
- National Soil Survey Office (NSSO), 1996. Soil Species of China, vol. 6. China Agriculture Press, Beijing (in Chinese).
- National Soil Survey Office (NSSO), 1998. Soil Species of China. China Agriculture Press, Beijing. (in Chinese).
- Ni, J., 2002. Effects of climate change on carbon storage in boreal forests of China: a local perspective. *Clim. Change* 55, 61–75.
- Ni, J., 2003. Net primary productivity in forests of China: scaling-up of national inventory data and comparison with model predictions. *For. Ecol. Manag.* 176, 485–495.
- Ni, J., Sykes, M.T., Prentice, I.C., Cramer, W., 2000. Modelling the vegetation of China using the process-based equilibrium terrestrial biosphere model BIOME3. *Glob. Ecol. Biogeogr.* 9, 463–479.
- Ni, J., Zhang, X.S., Scurlock, J.M.O., 2001. Synthesis and analysis of biomass and net primary productivity in Chinese forests. *Ann. For. Sci.* 58, 351–384.
- Norby, R.J., Gunderson, C.A., Wullschlegler, S.D., O'Neill, E.G., McCracken, M.K., 1992. Productivity and compensatory responses of yellow-poplar trees in elevated CO₂. *Nature* 357, 322–324.
- Norby, R.J., Wullschlegler, S.D., Gunderson, C.A., Johnson, D.W., Ceulemans, R., 1999. Tree responses to rising CO₂: implications for the future forest. *Plant Cell Environ.* 22, 683–714.
- Norby, R.J., Delucia, E.H., Gielen, B., Calfapietra, C., Giardina, C.P., King, J.S., Ledford, J., McCarthy, H.R., Moore, D.J.P., Ceulemans, R., 2005. Forest response to elevated CO₂ is conserved across a broad range of productivity. *PNAS* 102, 18052–18056.
- Oechel, W.C., Cowles, S., Grulke, N., Hastings, S.J., Lawrence, B., Prudhomme, T., Riechers, G., Strain, B., Tissue, D., Vourlitis, G., 1994. Transient nature of CO₂ fertilization in Arctic tundra. *Nature* 371, 500–503.
- Owensby, C.E., Coyne, P.L., Auen, L.M., 1993. Nitrogen and phosphorus dynamics of a tallgrass prairie ecosystem exposed to ambient and elevated CO₂. *Plant Cell Environ.* 16, 843–850.
- Pacala, S.W., Hurtt, G.C., Baker, D., Peylin, P., Houghton, R.A., Birdsey, R.A., Heath, L., Sundquist, E.T., Stallard, R.F., Ciais, P., et al., 2001. Consistent land-atmosphere-based U.S. carbon sink estimates. *Science* 292, 2316–2320.
- Pan, Y.D., Luo, T.X., Birdsey, R., Hom, J., Melillo, J.M., 2004. New estimate of carbon storage and sequestration in China's forests: effects of age-class and method on inventory-based carbon estimation. *Clim. Change* 67, 211–236.
- Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J.C., Seastedt, T., Garcia Moya, E., et al., 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Glob. Biogeochem. Cycles* 7, 785–809.
- Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Schimel, D.S., Hall, D.O., 1995. Impacts of climate change on grassland production and soil carbon worldwide. *Glob. Chang. Biol.* 1, 13–22.
- Peng, C.H., 2000. From static biogeographical model to dynamic global vegetation model: a global perspective on modelling vegetation dynamics. *Ecol. Model.* 135, 33–54.
- Peng, C.H., Apps, M.J., 1997. Contribution of China to the global carbon cycle since Last Glacial Maximum: reconstruction from paleovegetation maps and an empirical biosphere model. *Tellus* 49B, 393–408.
- Peng, C.H., Apps, M.J., 1998. Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in the Central of Canada: II sensitivity to climate change. *Glob. Biogeochem. Cycles* 12, 393–402.
- Peng, C.H., Apps, M.J., 1999. Modeling response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes. *Ecol. Model.* 122, 175–193.
- Peng, C.H., Liu, J., Dang, Q., Apps, M.J., Jiang, H., 2002. TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. *Ecol. Model.* 153, 109–130.
- Piao, S.L., Fang, J.Y., Zhou, L.M., 2003. Interannual variations of monthly and seasonal normalized difference vegetation index (NDVI) in China from 1982 to 1999. *J. Geophys. Res.* 108 (D14), 4401. doi:10.1029/2002JD002848.
- Piao, S.L., Fang, J.Y., Zhou, L.M., Zhu, B., Tan, K., Tao, S., 2005. Changes in vegetation net primary productivity from 1982 to 1999 in China. *Glob. Biogeochem. Cycles* 19 (GB2027) doi:10.1029.
- Piao, S.L., Ciais, P., Friedlingstein, P., Peylin, P., Reichstein, M., Luysaert, S., Margolis, H., Fang, J.Y., Barr, L., Chen, A.P., Grelle, A., Hollinger, D., Laurila, T., Lindroth, A., Richardson, A.D., Vesala, T., 2008. Net carbon dioxide losses of northern ecosystems in response to autumn warming. *Nature* 451, 49–52.
- Polglase, P.J., Wang, Y.P., 1992. Potential CO₂-enhanced carbon storage by the terrestrial biosphere. *Aust. J. Bot.* 40, 641–656.
- Ryan, M.G., 1991. The effects of climate change of plant respiration. *Ecol. Appl.* 1, 157–167.
- Ryan, M.G., Lavigne, M.B., Gower, S.T., 1997. Annual carbon cost of autotrophic respiration in boreal forest ecosystems in relation to species and climate. *J. Geophys. Res.* 102 (D24), 28871–28883.
- Saxe, H., Ellsworth, D.S., Heath, J., 1998. Tree and forest functioning in an enriched CO₂ atmosphere. *New Phytol.* 139, 395–436.
- Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häerli, C., Linie, M.A., Appenzeler, C., 2004. The role of increasing temperature variability in European summer heatwaves. *Nature* 427, 332–335.
- Schimel, D.S., House, J.I., Hibbard, K.A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B.H., Apps, M.J., Baker, D., Bondeau, A., et al., 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature* 414, 169–172.
- Schmitt, M.R., Edwards, G.E., 1981. Photosynthetic capacity and nitrogen use efficiency of maize, wheat, and rice: a comparison between C3 and C4 photosynthesis. *J. Exp. Bot.* 32, 459–466.
- Schroeder, P.E., 1992. Carbon storage potential of short rotation tropical tree plantations. *For. Ecol. Manag.* 50, 31–41.
- Shao, G.F., 1996. Potential impacts of climate change on a mixed broadleaved-Korean pine forest stand: a gap model approach. *Clim. Change* 34, 263–268.
- Shao, G.F., Bugmann, H., Yan, X., 2001. A comparative analysis of the structure and behavior of three gap models at sites in northeastern China. *Clim. Change* 51, 389–413.
- Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., et al., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Glob. Chang. Biol.* 9, 161–185.
- Steele, S.J., Gower, S., Vogel, J.G., Norman, J.M., 1997. Root mass, net primary production and turnover in aspen, jack pine and black spruce forests in Saskatchewan and Manitoba, Canada. *Tree Physiol.* 17, 577–587.
- Tans, P.P., Fung, I.Y., Takahashi, T., 1990. Observational constraints on the global atmospheric CO₂ budget. *Science* 247, 1431–1438.
- Taylor, J.A., Lloyd, J., 1992. Sources and sinks of atmospheric CO₂. *Aust. J. Bot.* 40, 407–418.
- Tjoelker, M.G., Oleksyn, J., Reich, P.B., 1999. Acclimation of respiration to temperature and CO₂ in seedling of boreal tree species in relation to plant size and relative growth rate. *Glob. Chang. Biol.* 49, 679–691.
- Tognetti, R., Cherubini, P., Innes, J.L., 2000. Comparative stem-growth rates of Mediterranean trees under background and naturally enhanced ambient CO₂ concentrations. *New Phytol.* 146, 59–74.
- Vitousek, P.M., Howarth, R.W., 1991. Nitrogen limitation on land and in the sea: how can it occur? *Biogeochemistry* 13, 87–115.
- Wang, C.K., Gower, S.T., Wang, Y.H., Zhao, H.X., Yan, P., Bond-Lamberty, B.P., 2001. The influence of fire on carbon distribution and net primary production of boreal *Larix gmelinii* forests in north-eastern China. *Glob. Chang. Biol.* 7, 719–730.
- Wang, S.Q., Tian, H.Q., Liu, J., Pan, S., 2003. Pattern and change of soil organic storage in China: 1960s–1980s. *Tellus* 55B, 416–427.
- Wang, C.K., Yang, Y., Zhang, Q., 2006. Soil respiration in six temperate forests in China. *Glob. Chang. Biol.* 12, 2103–2114.
- Weber, M.G., Flannigan, M.D., 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. *Environ. Rev.* 5, 145–166.
- Wong, S.C., 1979. Elevated atmospheric partial pressure of CO₂ and plant growth. 1. Interaction of nitrogen nutrition and photosynthetic capacity in C3 and C4 plants. *Oecologia* 44, 68–74.
- Wu, H.B., Guo, Z.T., Peng, C.H., 2003a. Land use induced changes of organic carbon storage in soils of China. *Glob. Chang. Biol.* 9, 305–315.
- Wu, H.B., Guo, Z.T., Peng, C.H., 2003b. Distribution and storage of soil organic carbon in China. *Glob. Biogeochem. Cycles* 17 (2), 1048.

- Waring, R.H., McDowell, N., 2002. Use of a physiological process model with forestry yield tables to set limits on annual carbon balances. *Tree Physiol.* 22, 179–188.
- Woodward, F.I., Beerling, D.J., 1997. The dynamics of vegetation change: health warmings for equilibrium 'Dodo' models. *Glob. Ecol. Biogeogr.* 6, 413–418.
- Wullschlegel, S.D., Tschaplinski, T.J., Norby, R.J., 2002. Plant water relations at elevated CO₂ – implications for water-limited environments. *Plant Cell Environ.* 25, 319–331.
- Xiao, X.M., Melillo, J., Kicklighter, D.W., Pan, Y., McGuire, A.D., Helfrich, J., 1998. Net primary productivity of terrestrial ecosystems in China and its equilibrium response to changes in climate and atmospheric CO₂ concentration. *Acta Phytocol. Sin.* 22, 97–118.
- Yang, L., Li, W., 2003. The underground root biomass and C storage in different forest ecosystems of Changbai Mountains in China. *J. Nat. Resour.* 18, 204–209.
- Zhang, X.S., Yang, D.A., 1993. A study on climate–vegetation interaction in China: the ecological model for global change. *Coenoses* 8, 105–119.
- Zhao, M., Zhou, G.S., 2005. Estimation of biomass and net primary productivity of major planted forests in China based on forest inventory data. *For. Ecol. Manag.* 207, 295–313.
- Zhou, Y.L., 1997. *Geography of the vegetation in Northeast of China*. Science Press, Beijing, China.
- Zhou, X.L., Peng, C.H., Dang, Q.L., 2004. Assessing the generality and accuracy of the TRIPLEX model using in situ data of boreal forests in central Canada. *Environ. Model. Softw.* 19, 35–46.
- Zhou, X.L., Peng, C.H., Dang, Q., 2005a. Predicting forest growth and yield in northeastern Ontario using the process-based carbon dynamic model of TRIPLEX1.0. *Can. J. For. Res.* 35, 2268–2280.
- Zhou, X.L., Peng, C.H., Dang, Q.L., Chen, J., Parton, S., 2005b. A simulation of temporal and spatial variations in carbon at landscape level: a case study for Lake Abitibi Model Forest in Ontario, Canada. *Mitig. Adapt. Strategies Glob. Chang.* 12, 525–543.
- Zhou, X.L., Peng, C.H., Dang, Q.L., 2006. Formulating and parameterizing the allocation of net primary productivity for modeling overmature stands in boreal forest ecosystems. *Ecol. Model.* 195, 264–272.
- Zhu, B., 2005. Carbon stocks of main forest ecosystems in Northeast China. MS Thesis, Peking University, Beijing.