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Carbon Dynamics in Woody Biomass of Forest Ecosystem in China with Forest Management Practices under Future Climate Change and Rising CO_2 Concentration

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Abstract: It is critical to study how different forest management practices affect forest carbon sequestration under global climate change regime. Previous researches focused on the stand-level forest carbon sequestration with rare investigation of forest carbon stocks influenced by forest management practices and climate change at regional scale. In this study, a general integrative approach was used to simulate spatial and temporal variations of woody biomass and harvested biomass of forest in China during the 21st century under different scenarios of climate and CO_2 concentration changes and management tasks by coupling Integrated Terrestrial Ecosystem Carbon budget (InTEC) model with Global Forest Model (G4M). The results showed that forest management practices have more predominant effects on forest stem stocking biomass than climate and CO_2 concentration change. Meanwhile, the concurrent future changes in climate and CO_2 concentration will enhance the amounts of stem stocking biomass in forests of China by 12%–23% during 2001–2100 relative to that with climate change only. The task for maximizing stem stocking biomass will dramatically enhance the stem stocking biomass from 2001–2100, while the task for maximum average increment will result in an increment of stem stocking biomass before 2050 then decline. The difference of woody biomass responding to forest management tasks was owing to the current age structure of forests in China. Meanwhile, the sensitivity of long-term woody biomass to management practices for different forest types (coniferous forest, mixed forest and deciduous forest) under changing climate and CO_2 concentration was also analyzed. In addition, longer rotation length under future climate change and rising CO_2 concentration scenario will dramatically increase the woody biomass of China during 2001–2100. Therefore, our estimation indicated that taking the role of forest management in the carbon cycle into the consideration at regional or national level is very important to project the forest carbon sequestration under future climate change and rising atmospheric CO_2 concentration.

Keywords: global forest model; carbon stock; forest management; rotation length; harvested biomass; future climate change

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1 Introduction

Regarding the observed increase in the atmospheric CO_2 concentration, one of the responses of scientists and policy makers to global climate change has been to explore the contribution of carbon sequestration by forest

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ecosystem to the global carbon budgets (Seely *et al*., 2002). Forest management practices, such as site preparation, species and provenance selection, fertilization, thinning, harvesting, and adjusting rotation length had important impacts on the forest carbon sequestration and harvested biomass (Pussinen *et al*., 2002; Ranatunga *et al*., 2008). Apart from the effects of forest management practices, the carbon in woody biomass of forest ecosystems were also affected by indirect human actives, such as the temperature and precipitation impacts of climate change and global increases in atmospheric CO_2 concentration (Mäkipää *et al*., 1999; Coomes *et al*., 2012). Forecasting changes in the forest carbon sequestration under different scenarios of climate change and forest management practices would be helpful to the sustainable use of China′s forest resources.

Recent climate change projections indicated that average surface air temperature relative to the 1980s is likely to increase by 1.1℃–6.4℃ by the end of the 21st century and the pattern of global precipitation will dramatically change in the next 100 years (IPCC, 2007). Meanwhile, the atmospheric concentration of CO_2 was expected to rise from the current 3.80×10^{-8} by volume and double by 2100, substantially altering the future global climate (IPCC, 2007). Changes in climate and atmospheric CO_2 concentration will affect plant physiology, and in turn carbon storage in forest biomass. The incremental increases in temperature will accelerate the photosynthesis rate, stimulate plant growth (Norby *et al*., 2005). Due to the complex interactions of climate change scenarios and CO_2 concentration, the carbon cycle of forest ecosystem can only be studied through with comprehensive models (Simioni *et al*., 2009). The dynamic responses of terrestrial carbon cycle to changes in climate and CO_2 concentration have been widely studied throughout the last decade (Cao and Woodward, 1998; Thornton *et al*., 2007). Concurrently, more and more studies integrated the role of forest management in estimating carbon stocks of forest ecosystems (Karjalainen *et al*., 2003; Zeeman *et al*., 2010; Shanin *et al*., 2011). Forest management practices affected the rate of carbon sequestration in forest ecosystems (Pussinen *et al*., 2002). Thereby, it could be a cost-effective mean of reducing net emissions and mitigating global climate change. Pacala and Socolow (2004) reported that with proper forest management, atmospheric CO_2 concentration could be stabilized at 5.50×10^{-8} by volume by 2050. It implied that forest management would play an important role in mitigating future climate warming.

Various methods, such as laboratory and field experiments (Jarvis, 1998), statistical analysis (Rathgeber *et al*., 2000), are used to project the effect of environmental factors on forest growth and carbon sequestration. Evaluating forest management strategies at large spatial and temporal scales are beyond the limit of traditional studies, which are often applied at stand-level and plot-level scales (Bu *et al*., 2008) and provide an estimation of carbon pools for a given time without evaluating the long-term effects of alternative management or natural disturbances (Wang *et al*., 2012). Integrated models can be an effective tool for decision makers to explore the combined effects of climate change and forest management practices on carbon dynamics in forest ecosystems (Joyce and Birdsey, 2000; Eggers *et al*., 2008). Joyce and Birdsey (2000) linked the Terrestrial Ecosystem Model (TEM) with an inventory-based forest sector model to assess national US forest resources responding to climate change. Karjalainen *et al*. (2003) analyzed the impacts of forest management and climate change on the carbon budget of European forest sector between 1990 and 2050 with the European Forest Information Scenario Model (EFISCEN) model. An individual-based stand-level model was used to simulate carbon dynamics of forest ecosystems in central Russia under different climate change scenarios and forest management regimes (Shanin *et al*., 2011). Eggers *et al*. (2008) used the EFISCEN model incorporated with the Lund-Potsdam-Jena (LPJ) vegetation model to assess the impact of changes in wood demand, climate and forest area on the European forest resources and carbon stocks during the 21st century. Shang *et al*. (2012) integrated a spatially explicit forest landscape model (Landscape Disturbance and Succession, LANDIS), a landscape habitat suitability model and a multi-criteria decision-making approach to evaluate management alternatives for a section of the Mark Twain National Forest in Missouri, USA.

China′s forests cover approximately 22% of total land area in 2010 and contain 4.75×10^{12} kg C in forest biomass in 1998 (Fang *et al*., 2001). The effect of forest management practices on forest carbon dynamics in China have been investigated for several tree species at fine spatial scales by many researchers, such as Bu *et al*. (2008), Liu *et al*. (2011), Zhang *et al*. (2011), Wang *et al*.

(2012), Yao *et al.* (2012), Zhao *et al.* (2013). Bu *et al.* (2008) used the LANDIS model to evaluate the effects of the projected climate warming on potential changes in species′ coverage, area harvested and species harvested in northeastern China. Field data were combined with the forest ecosystem management model, Forestry and Environmental Change Assessment (FORECAST), to estimate the impacts of different forest management strategies on carbon sequestration of evergreen broad-leaved plantation forests in the southeastern China (Wang *et al.*, 2012). Yao *et al.* (2012) used LANDIS model to evaluate the effects of 21 alternative forest management initiatives which were drafted for forests in the upstream region of the Hunhe River in the northeastern China. However, there is lacking of national level research studies in China. Fine scale patterns may generally contribute to the understanding of carbon flux trends at the stand spatial scale whereas regional or national carbon dynamics are more beneficial for China′s national decision makers. Furthermore, when climate is changing in the future, the quantitative evaluation of forest management practice becomes an ecological and economically important issue in China. As a result, we utilized scenario analysis to investigate how certain changes in forest management and climate change can influence future forest woody (stem) biomass in China. The objectives of this study are to estimate the woody biomass and harvested biomass of forest ecosystems in China during 2001–2100 and explore the interactive effects of climate and atmospheric CO_2 concentration change and forest management on forest woody biomass and harvested biomass at national scale.

2 Materials and Methods

2.1 Study area

As the third largest country in the word, China encompasses a broad range of climates, from tropical to subarctic/alpine and from rainforest to desert (Fang *et al.*, 2003). Mean annual temperature (MAT) and mean annual precipitation (MAP) of China from 1971 to 2000 are 6.7℃ and 636 mm, respectively (Yu *et al.*, 2004). According to State Forestry Administration (1999) report, there are 1.59×10^6 km^2 forest land. The spatial distribution of forest types in China is shown in Fig. 1 (Wang *et al.*, 2011).

2.2 Data and processing

2.2.1 Climate data

Climate data, mean annual temperature, mean temperature in growing season and mean annual precipitation were used in the ecosystem model. Historical climate data from 1901 to 1998 was developed from 0.5° global dataset established by the UK Climate Research Unit. Data during 1999–2009 were interpolated with the Australian National University Spline (ANUSPLIN) (Hutchinson, 2002) package to 1-km pixel from station data (680 stations) provided by the Chinese National Meteorological Information Centre. The projected climate (2010–2100) at 1° spatial resolution was the average outputs of several general circulation models from the IPCC A1B emissions scenario (Giorgi and Mearns, 2002; 2003; Xu *et al.*, 2009). To make down-scaling the climate model output, 2001–2009 projected climates at 1° spatial resolution were also used. The additive departure for temperature and multiplicative departures for precipitation during 2010–2100 relative to the 2001–2009 projected mean climates were interpolated to 1 km resolution, respectively (Ju *et al.*, 2007). The difference between observed mean climate data and projected mean climate data during 2001–2009 were applied to the original future climate data to produce effective projected climate data during 2010–2100. Figure 2 shows the temporal trends of national average MAT and MAP. In the future, temperature will significantly increase while precipitation also shows an increasing trend, but with a smaller magnitude compared with temperature.

2.2.2 Vegetation and soil texture data

The land cover map was derived from a nationwide land use map at a 30 m resolution, interpreted from Landsat TM images and a 1∶2 500 000 vegetation map. All forest types were delineated into three main cover types (coniferous forest, deciduous forest, and mixed forest). Soil texture data (clay, silt, sand factions) to a depth of 30 cm was produced by using 2473 soil profiles from the second national soil survey conducted in the 1980s. Referenced NPP in 2001 was simulated by Feng *et al.* (2007) using the Boreal Ecosystems Productivity Simulator (BEPS) model which was run at daily steps with remotely sensing leaf area index (LAI) and meteorological data as inputs. It has been validated by using a NPP database created by Luo (1996) according to field measurements. The referenced LAI map was derived

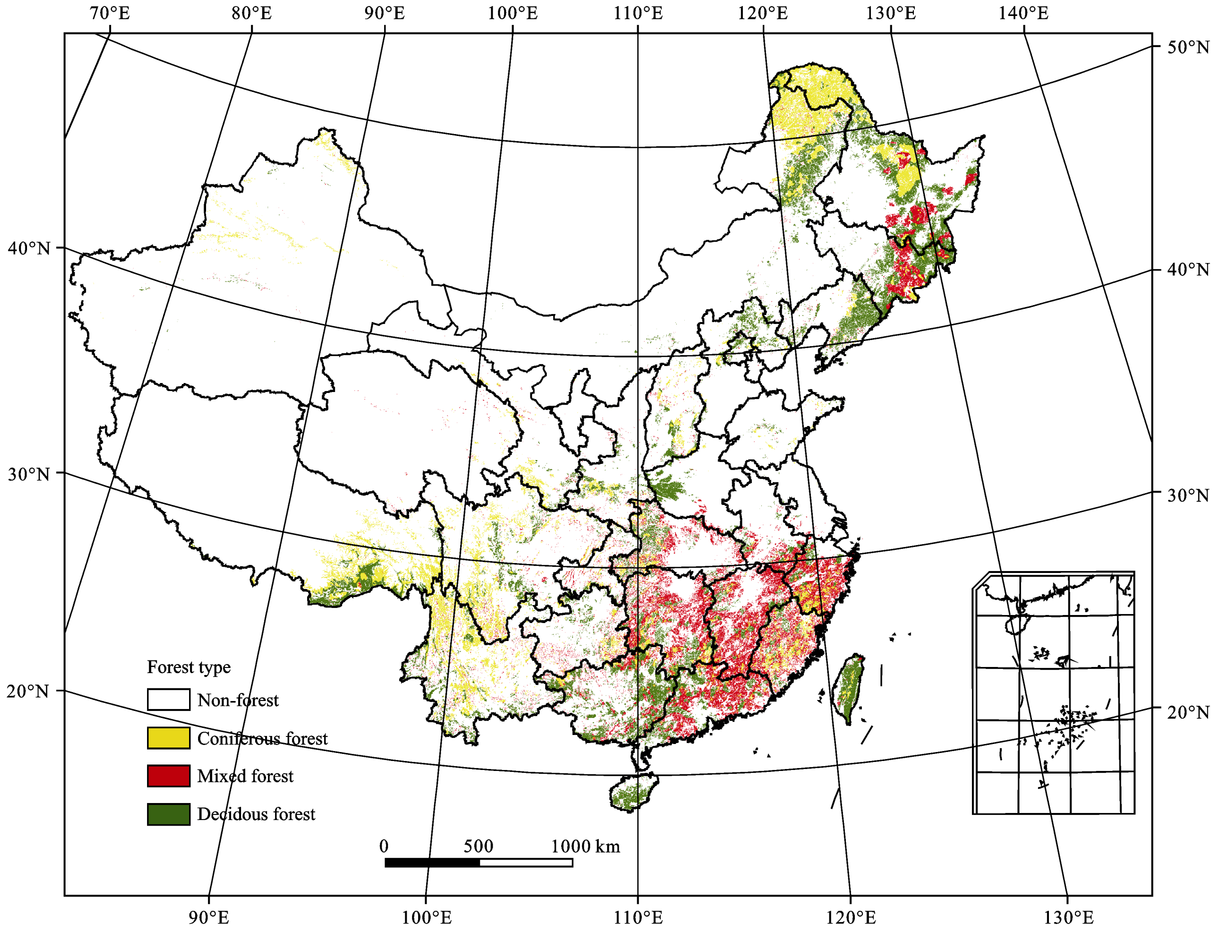

Fig. 1 Spatial distribution of forest in China

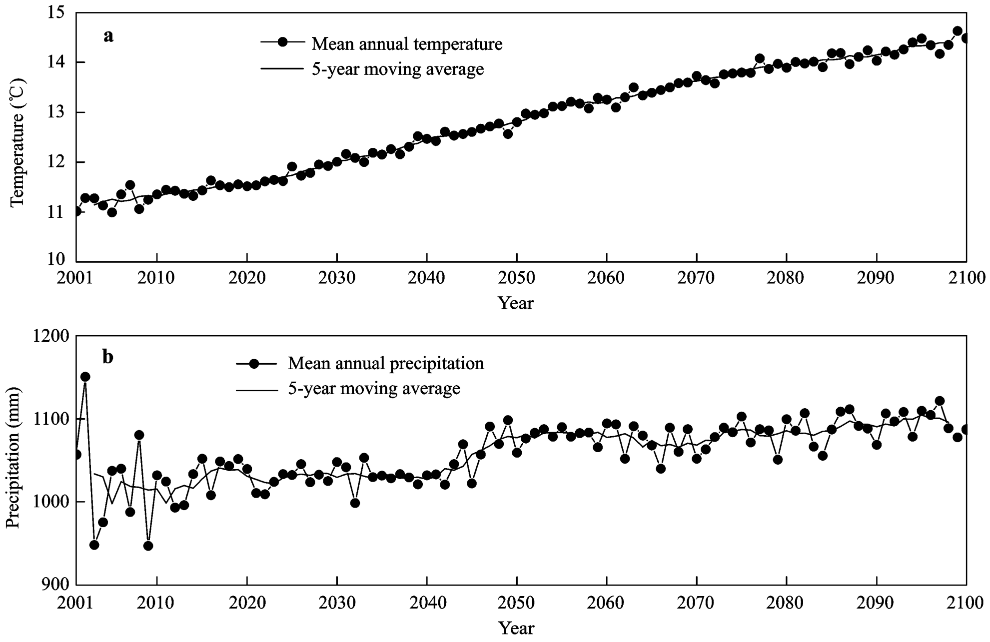

Fig. 2 Trends of average mean annual temperature (a) and mean annual precipitation (b) in China observed from 2001–2009 and projected by general circulation models from IPCC under A1B scenario for period of 2010 to 2100

from cloud-free composite images of the Moderate Resolution Imaging Spectroradiometer (MODIS) in 2001. A map of forest stand age in 2001 was created by using the data of the fourth national forest inventory conducted during the period from 1989 to 1993. Table 1 illustrates the age structure of three major forest types in China, which indicates that China′s forests were primarily comprised of stands aged 20–40 years.

2.2.3 Atmospheric CO_2 concentration and nitrogen deposition

Nitrogen deposition data under future climate scenarios were calculated from the measured deposition in 2001 (Wang *et al*., 2007) and future emissions under the assumption that the national emissions would increase by 100% (Ju *et al*., 2007). Atmospheric CO_2 concentration were from Chen *et al*. (2000) for period of 1901–1995 and from Waliguan Baseline Observatory (36°17′N, 100°54′E, 3816 m above sea level) in the inland plateau of the western China for period of 1996–2001 (Zhou *et al*., 2005). The remaining data under future climate were derived from the IPCC A1B emissions scenario.

2.3 Methods

2.3.1 InTEC model

The Integrated Terrestrial Ecosystem Carbon budget (InTEC) model was used as a tool for this study. It is a process model that integrates the effects of multiple factors (growing season length, temperature, precipitation, atmosphere CO_2 concentration, nitrogen deposition and disturbance) on carbon uptake by forests (Chen *et al*., 2000). This model iteratively calculates interannual variability of Net Primary Productivity (NPP) through temporally and spatially scaling up from instantaneous leaf-level Farquhar′s model (Farquhar *et al*., 1980). Dynamics of soil carbon and nitrogen was simulated by using the method adopted from Century model (Parton *et al*., 1993). In the calculation of NPP, the integrated effects of CO_2 concentration, nitrogen deposition, climate, and forest age were taken into consideration (Ju *et al*., 2007). NPP in a referenced year of 2001 was used as a benchmark to tune the initial NPP. The tuning continued until the absolute value of the difference between NPP from InTEC and that from BEPS was smaller than a threshold, 1% of the NPP value from BEPS. The InTEC model was run forward to simulate annual NPP and carbon budget during the period from 1901 to 2100, with the consideration of integrated effects of multiple factors on forest carbon cycling after the initialization. NPP and stand age in the initial year of 1900 along with mean climatic conditions prior to industrialization were employed to initialize biomass and soil carbon pools (Ju and Chen, 2005). Furthermore, it was driven by spatial datasets, such as meteorological data, soil texture (clay and silt), remote sensing data (land cover and LAI), and temporal datasets (CO_2 concentration and nitrogen deposition). Detailed description about the InTEC model, state variables, parameters, and data pre-processing methods are reported in Chen *et al*. (2000) and Ju *et al*. (2007). Due to lacking of available tree species specific growth data, the outputs for the InTEC model are restricted to general forest types such as coniferous, deciduous, and mixed forest.

The InTEC model has been previously validated and used in Canada: 1) to estimate the carbon balance of forests for the period 1895–1996 (Chen *et al*., 2000); 2) to analyze the spatial and temporal scales of carbon source and sink for the period 1901–1998 (Chen *et al*., 2003); 3) to simulate the distribution of soil carbon stocks of forests and wetlands (Ju and Chen, 2005); 4) to explore the hydrological effects on carbon cycles of forests and wetlands (Ju *et al*., 2006); 5) to simulate the integrated effect of climate, CO_2 and disturbance on the soil carbon in forests and wetlands (Ju and Chen, 2008); 6) to study the response of carbon cycle in forests and wetlands to variations of soil water content (Ju *et al*., 2010); and 7) to simulate the long-term carbon balance in a boreal landscape in the eastern Canada (Govinda *et al*., 2011).

The InTEC has been applied for China′s forests in several studies, such as Shao *et al*. (2007), Yang *et al*.

Table 1 Age structure of three major forest types in China

Forest type	Percentage of each age class (%)								
	1–10 year	10–20 year	20–40 year	40–60 year	60–80 year	80–100 year	100–120 year	120–140 year	>140 year
Coniferous forest	1.3	5.9	27.5	19.7	12.5	16.8	9.5	3.9	2.8
Mixed forest	2.6	13.6	37.5	26.4	12.7	4.8	1.2	0.6	0.6
Deciduous forest	2.8	24.1	55.5	8.8	4.7	2.3	1.1	0.4	0.2

(2007). It has been used to estimate the historical and future carbon dynamics of forests (Ju *et al.*, 2007; Wang *et al.*, 2007) and assess the potential of carbon sequestration of forests in the northeastern China (Thomas *et al.*, 2007) and in Liping County, China (Caldwell *et al.*, 2007). The age-dependent change of NPP has been used to improve the accuracy of model simulation of carbon dynamics for several typical forest ecosystems in China (Wang *et al.*, 2011).

2.3.2 G4M model

The global forest model (G4M) (Kindermann *et al.*, 2006; 2008; Gusti, 2010) is a geographically explicit model that simulates decisions made by virtual land owners on deforestation and afforestation and takes into account the profitability of forestry and agriculture. It contains a generic forest growth function which allows for the creation of a forest with specified environmental and management parameters (growth function parameters, mean annual increment (MAI), stand density, rotation length, harvested biomass, forest area and age structure information) (Gusti, 2010). The increment functions are able to describe the 1) total carbon production (TCP) of stemwood per hectare at increments optimal stand density ($\mathrm{SD_{opt}}$) depending only on age; 2) estimate the managed stand density; 3) the maximum possible stand density; 4) the tree size (diameter at breast height (DBH), height), and 5) the influence of stand density on TCP and DBH increment (Kindermann *et al.*, 2006; 2008; Gusti, 2010). Detailed calculation process is showed as follows.

(1) Total carbon production

TCP at stand age (*t*) can be described as:

$$TCP_t = TCP_{\max} \times \exp(k \times \ln^2(t / t_{\max})) \tag{1}$$

where TCP_t is the *TCP* at stand age *t*; $TCP_{\max}$ is the maximum *TCP* reached at stand age $t_{\max}$; *k* is a factor describing the shape of the increment curve.

The increment optimal harvesting time t_{opt} can be calculated with Equation (2) by *k* and $t_{\max}$,

$$t_{\mathrm{opt}} = t_{\max} \times \exp(0.5 / k) \tag{2}$$

Mean annual increment (*MAI*) is equal to the ratio of *TCP* at optimal harvest time t_{opt} ($TCP_{t_{\mathrm{opt}}}$) to t_{opt}:

$$MAI = \frac{TCP_{t_{\mathrm{opt}}}}{t_{\mathrm{opt}}} \tag{3}$$

The relation of *MAI* with *k*, $t_{\max}$ and $TCP_{\max}$ are described with equations (4) to (6).

$$k = c_0 + c_1 \times \exp(c_2 \times MAI^{c_3}) \tag{4}$$

$$t_{\max} = c_4 + \frac{c_5}{1 + \exp(c_6 + c_7 \times MAI)} \tag{5}$$

$$TCP_{\max} = MAI \times t_{\max} \times \exp(0.25 / k) \tag{6}$$

All coefficients of functions, c_0–c_7 and the following c_8–c_{45} are set according to Kindermann *et al.* (2011).

(2) Maximum stand density

Forest biomass with low thinning (removal of dead trees) at a specific age is the total carbon production subtracted by the biomass of dead and removed trees until this age. The fraction of carbon in the living biomass ($CMax_t$) compared to the *TCP* is described with Equation (7):

$$\frac{CMax_t}{TCP_t} = (cc_0 + cc_1 \times \ln(\frac{t}{t_{\mathrm{opt}}})) \times (1 - cc_2 \times \frac{t}{t_{\mathrm{opt}}})^{c_{21}} \tag{7}$$

$$cc_0 = c_8 + \frac{c_9}{1 + \exp(c_{10} + c_{11} \times MAI)}$$

$$cc_1 = \frac{c_{12}}{1 + \exp(c_{13} + c_{14} \times MAI)} + \frac{c_{15}}{1 + \exp(c_{16} + c_{17} \times MAI)}$$

$$cc_2 = c_{18} + c_{19} \times \exp(c_{20} \times MAI)$$

where $cc_2 \times (t / t_{\mathrm{opt}})$ defines the age when the biomass of all parts for a forest dies. If the estimated value of $CMax_t / TCP_t$ is lower than 0, $cc_2 \times (t / t_{\mathrm{opt}})$ is set to 0 or it is set to 1.

(3) Managed stand density

The managed stand density (SD) is defined as the density where 95% of the increment is fully stocked. It can be estimated by using Equation (8), which describes the increased dependent on stand density. The increment also depends on the actual stand density and Equation (8) is used to describe ratio of increment at a specific stand density (TCP_{SD}) and the increment at increment optimal stand density (TCP_{opt}).

$$\frac{TCP_{\mathrm{SD}}}{TCP_{\mathrm{opt}}} = \frac{cc_{11} - {cc_{11}}^{cc_6}}{cc_9} \tag{8}$$

$$cc_6 = 1 + \frac{t^{c_{36}}}{c_{37}} \times \frac{1}{c_{38} + c_{39} \times MAI^{c_{40}}}$$

$$cc_7 = 1 + \frac{c_{41}}{1 + c_{42} \times t^{c_{43}} \times \frac{1}{c_{44} + MAI^{c_{45}}}}$$

$$cc_8 = (\frac{1}{cc_6})^{\frac{1}{cc_6 - 1}}$$

$$cc_9 = cc_8 - cc_8^{\ cc_6}$$

$$cc_{10} = cc_8 \times cc_7$$

$$cc_{11} = cc_8 \quad \text{when} \quad cc_8 \le SD \times cc_{10}$$

$$cc_{11} = SD \times cc_{10} \quad \text{when} \quad cc_8 > SD \times cc_{10}$$

(4) Tree size

The height development (h) at age t is described in Equation (9)

$$h = c_{22} \times MAI^{c_{23}} \times (1 - \exp(c_{24} \times t))^{c_{25} \times MAI^{c26}} \qquad (9)$$

Meanwhile, the age when the height of 1.3 m ($t_{\mathrm{h}1.3}$) is reached can be estimated with Equation (10).

$$t_{\mathrm{h}1.3} = \frac{\ln(1 - \frac{1.3}{c_{22} \times MAIc_{23}}^{\frac{1}{c_{25} \times MAI^{c26}}})}{c_{24}} \qquad (10)$$

When forests are young (age < $t_{\mathrm{h}1.3}$), DBH is set to zero. In older ages, the average diameter of a full stocked stand (d_{fs}) is calculated by Equation (11).

$$d_{\mathrm{fs}} = cc_3 \times (1 - \exp(cc_4 \times (t - t_{\mathrm{h}1.3})))^{cc_5} \qquad (11)$$

$$cc_3 = c_{27} + c_{28} \times MAI$$

$$cc_4 = c_{29} \ / \ (1 + c_{30} \times MAI^{c_{31}})$$

$$cc_5 = c_{32} \ / \ (1 + c_{33} \times MAI^{c_{34}})$$

(5) Stand density dependency

The stem diameter estimation in Equation (11) describes diameter development over time in fully stocked stands, indicating that stand density effects diameter and volume increment. As a result, the diameter of a tree grown permanently under specific stand density (d_{SD}) other than full stocked stand densities can be calculated by Equation (12).

$$\frac{d_{\mathrm{SD}}}{d_{\mathrm{fs}}} = 2 - SD^{c_{35}} \qquad (12)$$

The G4M model has been used to simulate the land use and forest management on a global spatial scale (Gusti and Kindermann, 2011) and applied to the assessment of potential woody biomass and increments under different management and climate scenarios in the European Union (Kindermann *et al.*, 2011). In this study, the forest growth and management module of G4M model was used to explore the effect of forest management on forest stem stocking biomass and harvested biomass. The model incorporated two management tasks by determining rotation length to maximize MAI and sustainable harvest or maximum stocking biomass. Due to lacking of available tree species growth data, the output of the G4M model was limited to typical forest types such as coniferous, deciduous, mixed forest types.

2.3.3 Model simulation design

The initialization of InTEC model was implemented at two steps. Firstly, referenced NPP in 2001 was used to tune the initial NPP value in 1901. Secondly, the initialization of ecosystem carbon pools was based on the assumption that carbon dynamics was approximately in equilibrium prior to 1901 for forest stands younger than 100 years in 2001. For stands older than 100 years in 2001, the dynamic equilibrium is assumed to operate prior to the last disturbance before 1901 (Chen *et al.*, 2003; Ju and Chen, 2005). The model was run until carbon dynamics arrived at equilibrium using the average climate data during the period of 1901–1910 (Ju and Chen, 2005). After the initialization, the historical climate data (MAT, MAP, and growing season length), CO_2 concentration, and nitrogen deposition were used along with other data to drive the model to simulate the time series of annual NPP during 1901–2000. The InTEC model was run continuously during 2001–2100 with different scenarios under future climate and atmospheric composition changes, namely current climate and CO_2 concentration (scenario 1), changing climate and current CO_2 concentration (scenario 2), and changing climate and CO_2 concentration (scenario 3) (Table 2).

NPP simulated by the InTEC model with different climate and CO_2 inputs was used to calculate increment and then translated into MAI in the G4M model (equations (1)–(6)). In all simulations, annual NPP over every 10-year period was averaged to obtain decadal mean NPP during 2001–2100. The outputs of the forest management module in G4M were stem stocking biomass and harvested biomass at 10-year increments. No harvested biomass was obtained in 2001. We designed

Table 2 Design of simulation scenarios

Scenario number	Climate change scenario	Period for data used		Rotation length	Management task
		Climate change	CO_2 concentration change		
Scenario 1	Current climate and CO_2 concentration	2001	2001	Long	Maximum average increment Maximum average biomass
Scenario 2	Changing climate and current CO_2 concentration	2001–2100	2001	Long	Maximum average increment Maximum average biomass
Scenario 3	Changing climate and CO_2 concentration	2001–2100	2001–2100	Long/medium/short	Maximum average increment Maximum average biomass

scenarios using three climate change scenarios and three rotation length scenarios under two forest management tasks (maximum average increment and maximum average biomass) (Table 2). The changing climate and CO_2 concentration scenario consists of three rotation length scenarios with management practice changes: 1) long rotation length, rotation factor (Rot_Factor) equals to 1.00, which means use the optimal rotation length; 2) medium rotation length, rotation factor (Rot_Factor) equals to 0.75, which means 75% of the optimal rotation length; and 3) short rotation length, rotation factor (Rot_Factor) equals to 0.50, which means half of the optimal rotation length. Optimal rotation length for each forested pixel varied and was determined according to management tasks, existing stocking biomass, and harvested biomass (equations (2)–(5)). Model explored the sensitivity of long-term carbon stocks to management practices for forest types under changing climate and CO_2 concentration scenario.

3 Results and Analyses

3.1 Comparison of model outputs with measured data

A significant challenge for spatially explicit processed models is how to validate the simulated results. Traditional validation methods include using independent data to test the accuracy of model simulation at spatial and temporal aspects. Firstly, the InTEC model was validated at Qianyanzhou Station (26°44′48″N, 115°04′13″E) which is located in the mid-subtropical region of China. This ecological station belongs to the ChinaFLUX network and provides meteorological data and eddy covariance data. In general, simulated NPP was consistent with measured values, describing reasonable forest growth after afforestation at this site (Fig. 3).

Because processed models used in this study were applied at regional scales, the outputs covering a long period of time and a large scale were not spatial replicable and may go beyond with the observation at plot level (He *et al.*, 2002). Here, NPP simulated by InTEC model was also validated by using ground-based NPP measurements (Luo, 1996) for several different forest types. Luo (1996) used the allometric equations specific for certain forest types and regions to calculate biomass of tree stems, branches, foliage, and roots with stand diameter at breast height and height of each age group, and then estimated total tree biomass by the sum of the biomass of tree components. Plot live biomass based on the growth rates derived from stem analysis research

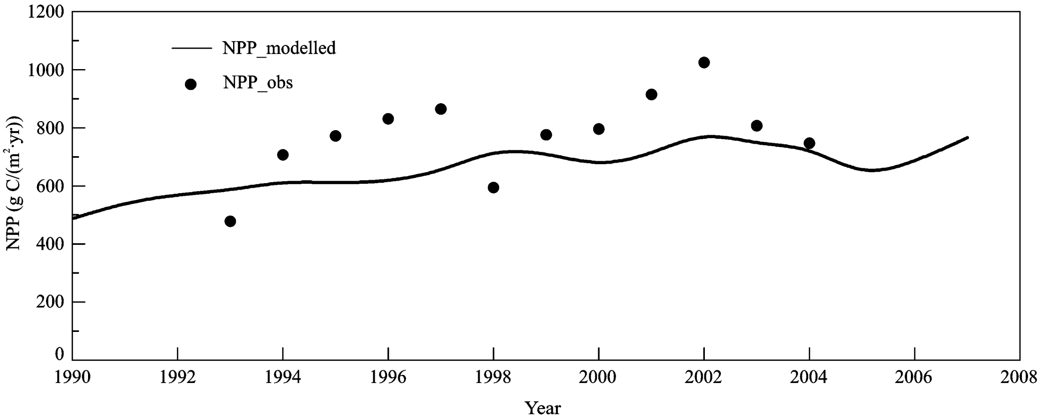

Fig. 3 Comparison of modeled NPP with measurements in Qianyanzhou Station

and leaf life span was used to estimate the plot NPP (Luo *et al.*, 2002). NPP simulated from the InTEC model was consistent with measurements (Table 3), indicating the ability of this model to simulate forest NPP across China.

3.2 Effects of climate change and atmospheric CO_2 concentration on stem stocking biomass and harvested biomass of forest during 2001–2100

Stem stocking biomass and harvested biomass were calculated under three NPP simulation scenarios (current climate and CO_2 concentration, changing climate and current CO_2 concentration, and changing climate and CO_2 concentration) and two management strategies. Figure 4 shows the time series of stem stocking biomass and harvested biomass during the 21st century. Average stem stocking biomass increased from 1.9 kg C/m^2 in 2001 to 7.6 kg C/m^2 in 2100 under current climate and maximum average biomass task while maximum average increment will result in an increment of stocking biomass before 2050 then decline (Fig. 4a and Fig. 4b). In the changing climate and current CO_2 con centration scenario, the goal was to maximize average increment during 2001–2100 resulted in a fluctuating stem stocking biomass in the range of 1.9–3.1 kg C/m^2 (Fig. 4a), with a total of 3.54×10^{12}–5.78×10^{12} kg C for the forested areas in China. Maximizing the stocking biomass resulted in an increase in the stem stocking biomass from 1.9 kg C/m^2 (3.54×10^{12} kg C for total biomass) to 11.2 kg C/m^2 (2.09×10^{13} kg C for total biomass) for changing climate and current CO_2 concentration scenario (Fig. 4b). The harvested biomass was projected to increase until the year 2070 and decreased following maximum increment during 2001–2100 (Fig. 4c), while the harvested biomass was keep stable but relative low for maximizing the stocking biomass (Fig. 4d). Under

Table 3 Comparison of mean modeled NPP (NPP_m) by using InTEC model and corresponding values (NPP_{obs}) compiled from dataset of Luo (1996) for several major forest types in China

Forest type	NPP_m (g C/(m^2·yr))	NPP_{obs} (g C/(m^2·yr))	*E* (%)
Cool temperate coniferous forest	386	386	0
Temperate deciduous broadleaved forest	451	501	–10
Subtropical broadleaved forest	579	690	–16
Temperate coniferous forest	446	412	8
Subtropical coniferous forest	591	667	–11
Temperate mixed forest	503	425	18

Note: Estimation error (*E*) is calculated by equation: $(NPP_m - NPP_{obs}) / NPP_{obs} \times 100\%$

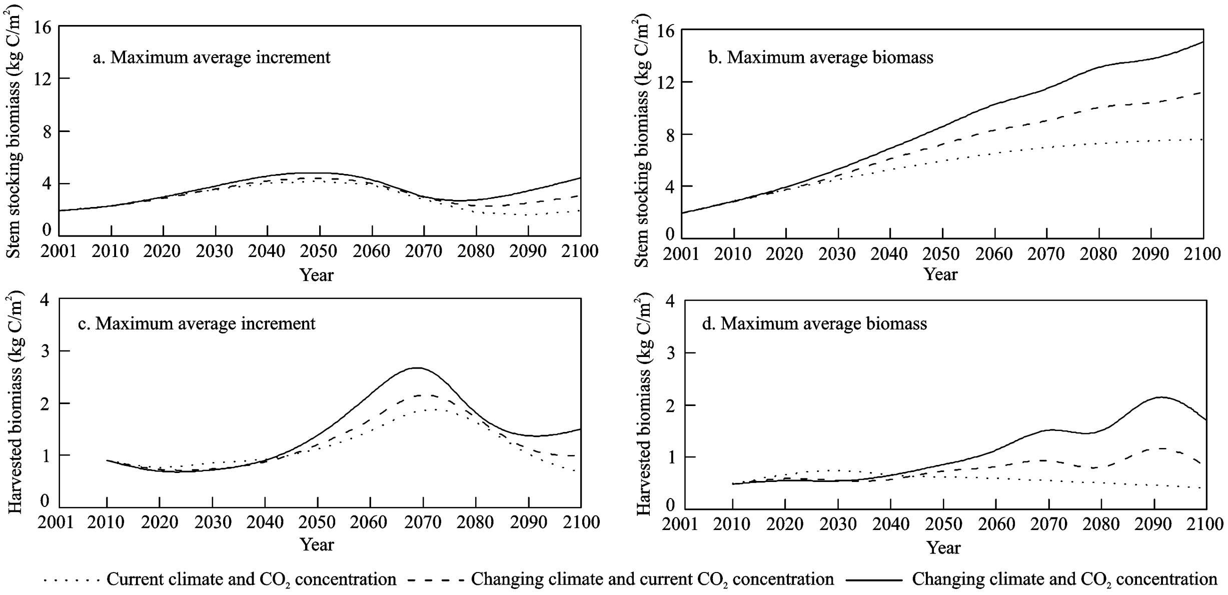

Fig. 4 Stem stocking biomass and harvested biomass for two forest management tasks under three climate change scenarios

changing climate and CO_2 concentration scenario, the trends of stem stocking biomass and harvested biomass for both management tasks during 2001–2100 are similar to those under changing climate and current CO_2 concentration scenario (Fig. 4). However, the increase in atmospheric CO_2 will enhance stem stocking biomass and harvested biomass for both forest management tasks. Climate change generally resulted in increasing stem stocking biomass and harvested biomass for two management tasks during the 21st century. Climate change will cause more carbon sequestration by forest ecosystems if maximum average biomass task instead of maximum average increment task will be taken. In addition, the combined effects of climate change and CO_2 fertilization on the average stem stocking biomass over the period of 2001–2100 are estimated to be 12%–23% higher than the effect of only climate under two forest management tasks (Fig. 4a and Fig. 4b).

The ratio of harvested biomass to the concurrent stem stocking biomass was also calculated under three climate change scenarios and two management tasks (Fig. 5). It indicated that the ratio of harvested biomass to stem stocking biomass will peak around 2070–2080 with the goal of maximum average increment, while the ratio will decrease during the simulation period as to maximum average biomass. The impact of climate change and CO_2 fertilization on this ratio behaved similar patterns. However, under current climate and CO_2 concentration, the ratio peak more lately or decrease faster comparing to another two climate change scenarios for two management tasks, respectively (Fig. 5).

Forests are mostly located in the south and northeast China. Figure 6 illustrates the spatial distribution of average stem stocking biomass and harvested biomass from 2001 to 2100 under changing climate and CO_2 concentration scenario and two management tasks. During the simulation period of 100 years, the mean value of stem stocking biomass will mainly ranged from 2.0 kg C/m^2 to 6.0 kg C/m^2; if the maximum average increment management strategy is taken, and that will mainly range from 6.0 kg C/m^2 to 25.0 kg C/m^2 if maximum average biomass is taken (Fig. 6a and Fig. 6c). The harvested biomass will be higher under the condition of maximum increment than that under the condition of maximum average biomass, especially in the southern China (Fig. 6b and Fig. 6d).

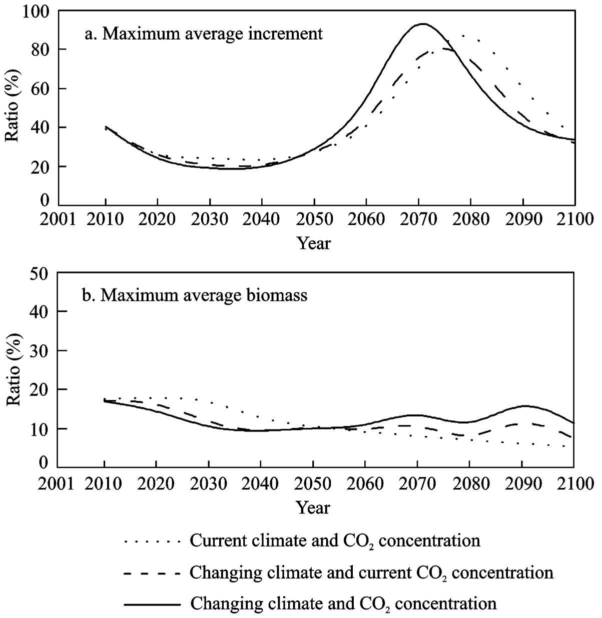

Fig. 5 Ratio of harvested biomass to stem stocking biomass for two forest management tasks under three climate change scenarios

3.3 Stem stocking biomass of different forest types during 2001–2100

If maximum average increment management strategy is taken, the stem stocking biomass of coniferous forest will change slightly with a mean value of 3.2 kg C/m^2 during the period from 2001 to 2100 while that of mixed forest and deciduous forest will reach peaks at the mid 21st century (Fig. 7a). The harvested biomass of mixed forest will be larger than that of coniferous and deciduous forests during 2030–2080 (Fig. 7c).

When maximum average biomass management strategy is implemented during the simulation period of 100 years, the trends of stem stocking biomass will be similar for all forest types, especially during the period of 2060–2100 (Fig. 7b). The harvested biomass of coniferous forest will be significantly larger than that of other two forest types over the whole study period (Fig. 7d).

3.4 Effect of rotation length on stem stocking biomass and harvested biomass of forest during 2001–2100

Figure 8 shows the effect of rotation length on stem stocking biomass and harvested biomass under two management tasks. With shorter rotation length (Rot_ Factor = 0.50), the stem stocking biomass will be relatively low under maximum average increment and more biomass could be harvested at the early stage of the 21st century (Fig. 8a). Maximum average increment resulted

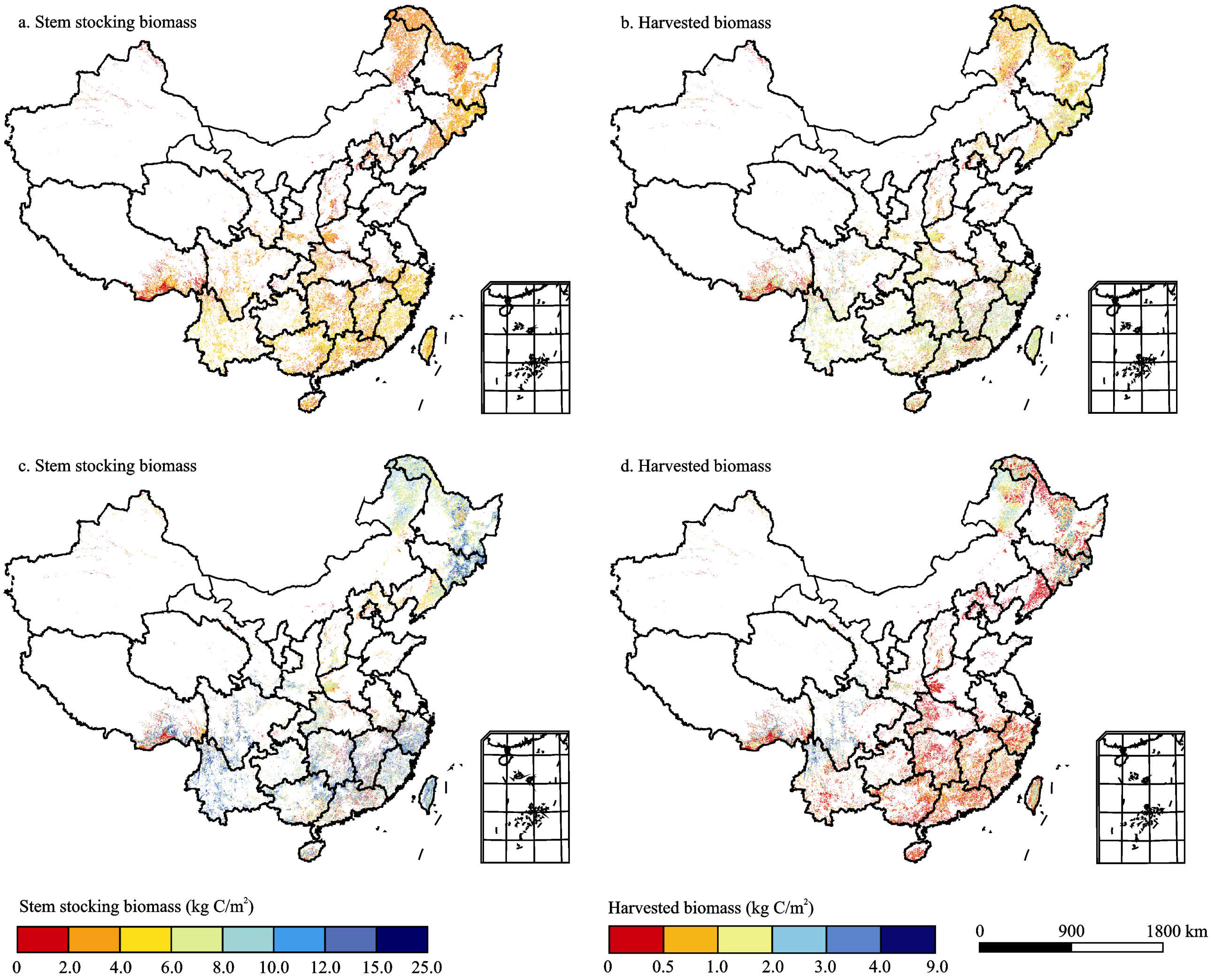

Fig. 6 Spatial distribution of average stem stocking biomass and harvested biomass over period from 2001 to 2100 under changing climate and CO_2 concentration scenario with two forest management tasks. a and b for maximum average increment management task; c and d for maximum average biomass management task

in the largest harvested biomass that reach the maximum values around 2070 by choosing long rotation lengths (Rot_Factor = 1.00) (Fig. 8c). Overall, the change in rotation length ranged from medium (0.75) to high (1.00) will cause average stem stocking biomass to increase by 43% during the simulation period (Fig. 8a). When maximum average biomass management task is implemented, the stem stocking biomass and the harvested biomass are very similar for the optimal rotation lengths of 0.75 and 1.00 during 2001–2100 (Fig. 8b and 8d). If the Rot_Factor equals to 0.50, stem stocking biomass will start to decrease in 2080 (Fig. 8b).

4 Discussion

In this study, we used a general integrative approach to simulate spatial and temporal variations of woody biomass and harvested biomass of forest in China during the 21st century under different scenarios of climate and CO_2 concentration changes and management tasks through coupling the InTEC model with G4M model. Processed models, such as InTEC model, have been widely used to explore the effects of climate and atmospheric composition changes on the forest carbon budgets (Chen *et al.*, 2003; Ju *et al.*, 2007; Wang *et al.*, 2007). However, even the large-scale carbon budget assessments with terrestrial biosphere model (Cramer *et al.*, 2001; McGuire *et al.*, 2001) did not take the effect of forest management practices into account. The forest growth and management model like G4M is able to describe management effect but can not account for the effects of environmental changes directly (Eggers *et al.*,

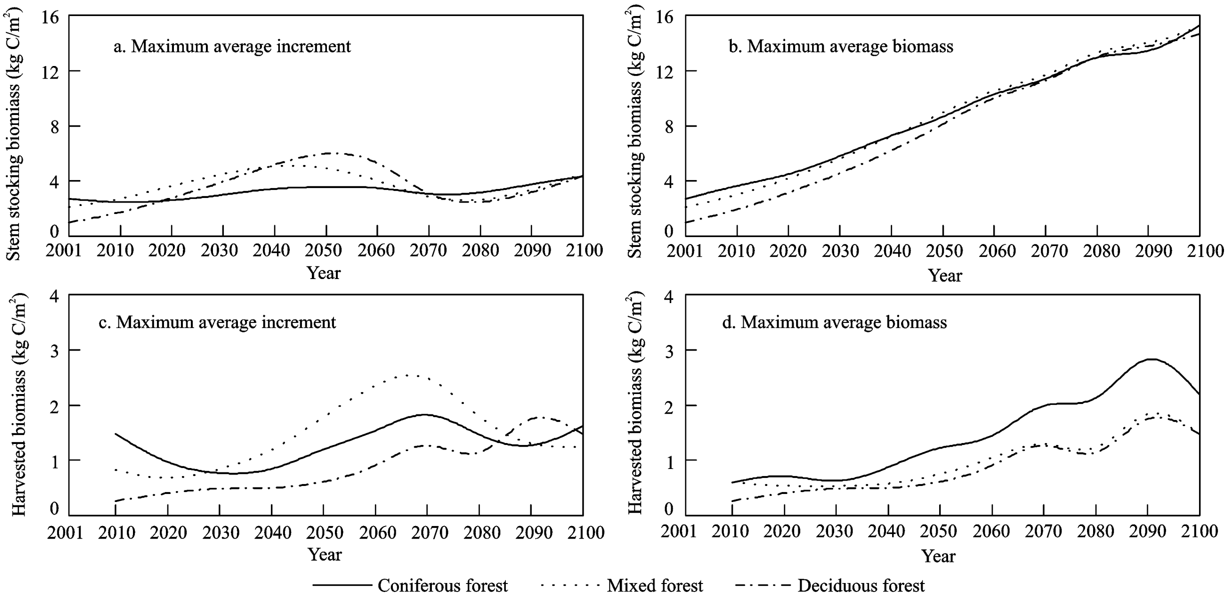

Fig. 7 Stem stocking biomass and harvested biomass of different forest types under changing climate and CO₂ concentration scenario with two forest management tasks

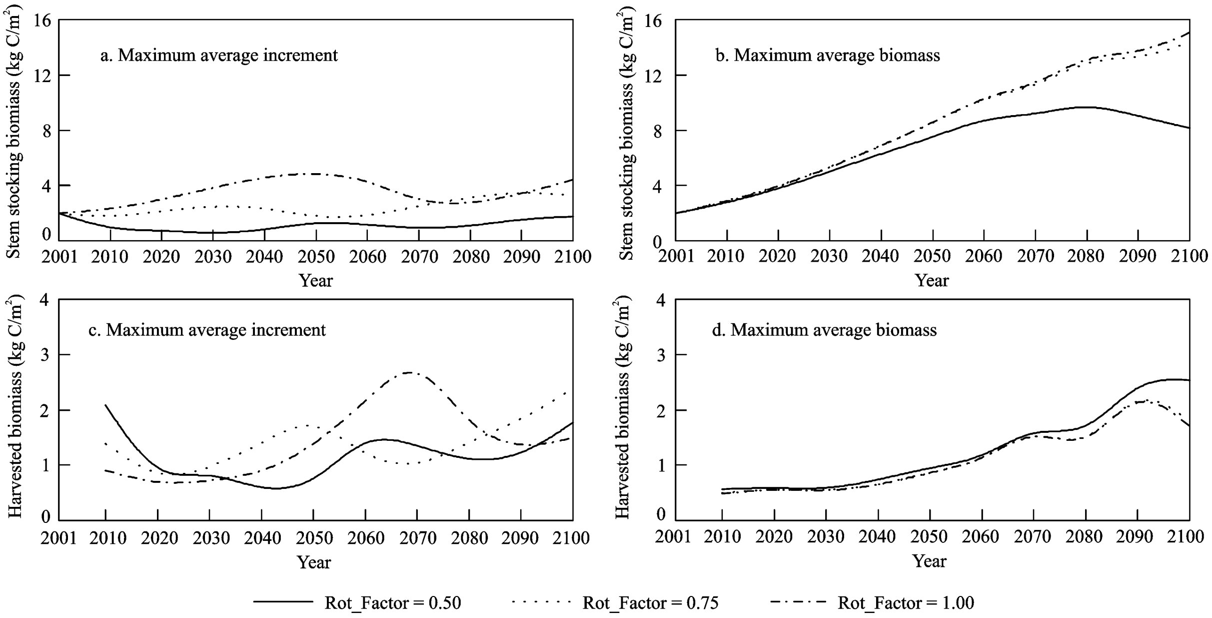

Fig. 8 Stem stocking biomass and harvested biomass for two forest management tasks and different rotation lengths (Rot_Factor equals to 0.50, indicating half of optimal rotation length; Rot_Factor equals to 0.75, indicating 75% of optimal rotation length; Rot_Factor equals to 1.00, which means optimal rotation length)

2008). By incorporating NPP projection derived from the InTEC model into G4M model, the integrated effects of environment changes and management on woody biomass and harvested biomass of China's forests during the 21st century were investigated.

4.1 Response of forest stem stocking biomass to climate change and increasing CO$_2$ concentration

Climate change generally resulted in increased stem stocking biomass and harvested biomass for all forest management tasks under consideration (Fig. 4). Climate influences the processes of vegetation, and in turn forest biomass. For example, increased temperature may metabolically enhance photosynthesis and stimulate plant forest biomass (Melillo *et al.*, 1993). For China, it has been projected that the mean annual temperature and annual precipitation during 2091–2100 will increase by 3.1℃ and 7.1% relative to the averages of 2001–2009, respectively (Fig. 2). Such future climate change implies longer and warmer growing seasons, which will lead to the acceleration of plant growth (Mäkipää *et al.*, 1999). Our simulations indicated that climate change will cause maximum increment of 1.2–3.6 kg C/m^2 in the stem stocking biomass under two forest management tasks.

High CO_2 concentration may increase plant growth through a process known as the 'CO_2 fertilization effect' (Ainsworth and Long, 2005), which had been proved with data from field experiments (Norby *et al.*, 2005), such as Free-Air CO_2 Enrichment (FACE). Long *et al.* (2004) reviewed the mechanism of this effect and suggested that increased CO_2 enhances the rate of carboxylation at Rubisco while inhibiting the oxygenation reaction and thus decreases photorespiratory loss of carbon. Several modeling studies have explored the possible impacts of future climate change and increasing atmospheric CO_2 concentration on the terrestrial carbon cycle (Cao and Woodward, 1998; White *et al.*, 2000; Cramer *et al.*, 2001; Berthelot *et al.*, 2002), which commonly reported that the combination of climate change and rising CO_2 concentration will enhance carbon sequestration by terrestrial ecosystem during the 21st century. In this study, the woody biomass of forest will increase with rising CO_2 concentration regardless of management tasks. Rising atmospheric CO_2 concentration and the doubling of nitrogen deposition coupled with climate change resulted in a faster woody biomass accumulation and more harvested biomass (Fig. 4). The peak of harvested biomass under changing climate and CO_2 concentration scenario will occur earlier than that under changing climate and current CO_2 concentration scenario when forest management aims at maximum average increment (Fig. 4c).

4.2 Response of forest stem stocking biomass to forest management practices

The forest management decisions will more significantly affect the time series of stem stocking biomass than different climate change scenarios (Fig. 4). When the goal of forest management is maximum average increment, the rotation length of forests should be relatively short, and then the harvested biomass will increase for the contribution of fast growth of young forest. The harvested biomass will reach peak around 2070–2080 (Fig. 4c). In 2001, forests in China are mostly in the 20–40 years age class, accounting for 41% of the total (Table 1). This implies that China's forests will reach the age of harvest in 50–70 years (Fig. 4c). If forest management aims at maximum average biomass, which is accomplished by long rotation length with low harvested biomass (Fig. 4b and Fig. 4d), the stem stocking biomass of forests will significantly increase during the 100 years and reach the highest values by the end of the 21st century (Fig. 4b). Although the absolute values showed some differences, the spatial and temporal pattern of the stem stocking biomass and harvested biomass under different forest management scenarios are quite similar (Fig. 4 and Fig. 6). If the management target is to produce as much wood as possible, forests will be younger and have less stem stocking biomass than a management target which maximum average biomass.

Differences in long-term trends of carbon stocks among forest types may be species dependent. In general, the carbon storage potential of a given species is dependent on the maximum stand biomass and the time required reaching that maximum (Seely *et al.*, 2002). Coniferous forests and mixed forests may be growing relatively quickly and reach maximum biomass early. Deciduous forests grow slower but obtain a higher maximum biomass (Fig. 7). The growth differences between coniferous forests and deciduous forests are also dependent on the differences in the dominant age class (Table 1). In general, the impact of forest management on the carbon stocks varies with forest types (Kaipainen *et al.*, 2004). Therefore, proper species selection under climate change and rising CO_2 concentration is important for the carbon sequestration by forests in the future.

The choice of rotation length is considered to be an effective forest management activity for controlling carbon stocks of forests (Liski *et al.*, 2001; Pussinen *et al.*, 2002). Many studies indicated that allowing forest stands to accumulate greater biomass through longer rotation has been an effective way of increasing carbon storage (Cooper, 1983; Seely *et al.*, 2002). Liski *et al.*, (2001) stated that the carbon stocks of trees increase with increasing rotation length, which is helpful for the reduction of greenhouse gas emissions (Kaipainen *et al.*, 2004). The study of a 20-year increment in current rotation lengths in European forests indicated that average carbon stocks of biomass increased by 6%–13% for pine forests and by 14%–67% for spruce forests (Kaipainen *et al.*, 2004). The study for European forests concluded that forest management played a more important role in the deciduous forests than in coniferous forests. Furthermore, increasing rotation length would also affect the harvested biomass. The longer rotation length would decrease the amount of harvest residues that could be used to produce bioenergy (Kaipainen *et al.*, 2004). In our study, the effect of altered rotation length on the harvested biomass was assessed according to forest management decisions (Fig. 8). Choosing longer rotation length will maximize average biomass and change from a long rotation length to medium rotation length will have little effect on the dynamic of stem stocking biomass and harvested biomass. However, if the management aiming at maximum average increment is implemented, changes in rotation length during 2001–2100 will influence the amount of stem stocking biomass and the stand age with peak harvested biomass. The reason for this phenomenon is that rotation length is relatively shorter for maximum average increment than for maximum average biomass. The selection of short rotation length results in substantial declines in long-term ecosystem carbon storage. As a result, choosing longer rotation length in the maximum increment scenario will increase the stem stocking biomass of forest in China, especially in middle of the 21st century. If the rotation length increases from medium (Rot_Factor = 0.75) to long (Rot_Factor = 1.00), the stem carbon stocks of forests will increase by 43%. This is due to the fact that the amount of wood annually harvested decreases with increasing rotation length. In addition, if we want to have wood ′as soon as possible′, Rot_Factor (0.75) is a better choice while Rot_Factor (1.00) may be helpful for us to gain wood ′as much as possible′.

4.3 Comparison of estimated stem stocking biomass and harvested biomass with other studies

Estimates were 1.9–2.2 kg C/m^2 and 1.9–2.8 kg C/m^2, respectively for the stem stocking biomass with the G4M model under changing climate and CO_2 concentration scenario for maximum average increment and maximum average biomass in 2005. The forest stocking biomass of China in 2005 was estimated 2.5 kg C/m^2 reported by FAO (2005). The forest cover of China in 2005 was about 1.97×10^6 km^2 (FAO, 2005) and it indicated that a total of 3.74×10^{12}–5.52×10^{12} kg C are stored in the stem wood of China′s forests. Unfortunately, our results on the effects of management practices on stem stocking biomass of forests under climate change could not be compared to any domestic measurements due to the lack of such kind of previous results in China. Meanwhile, since long-time series field measurements do not exist for the future climate change, it is not possible to validate the long-term prediction of models.

In this study, one of weaknesses is that we did not take into account the potential impact of forest management practices on carbon stocks of soil in forest ecosystems, because the G4M model is unable to simulate soil carbon dynamics, which plays an important role in the carbon budgets of entire forest ecosystems. It is necessary to consider the response of soil carbon pools to climate change, rising CO_2 concentration and management practices in the future studies (Eggers *et al.*, 2008).

4.4 Uncertainty analyses

Future climate used here were projected by climate models. It may contain uncertainties, which could be constrained by the integration outputs from several process models for more representation (Karjalainen *et al.*, 2003). In this study, we used the average output of several climate models to produce the projected climate and uncertainties in the future climate change scenarios could be reduced to some extent. Furthermore, NPP simulated by the InTEC model represents the effects of climate and CO_2 concentration changes on the carbon dynamics of forests in China. The G4M model was used to simulate the impact of management practices on the forest woody biomass under two forest management tasks. Due to data limitation, static forest distribution in China over the study period was assumed. In reality, afforestation, reforestation and deforestation have been dramatically occurring in China in recent decades, impacting the carbon cycle of forests in China significantly.

Meanwhile, extreme climatic events, such as drought, heat wave, and flood, may have greater impact on forest ecosystem than normal climate. For example, extreme drought caused forest productivity to decrease in response to stomatal closure (Ciais *et al.*, 2005; Zeng *et al.*, 2005), which can turn ecosystem from being carbon sink to source in temperate forest ecosystems (Ciais *et al.*, 2005). Our estimation can not reflect the effects of more extreme events in the future on forest carbon sequestration. Future researches should assess the effects of the change in extreme climatic events on the carbon balance of China′s forests.

5 Conclusions

Processed models are efficient tool when coupled with forest management models for evaluating the effect of management practices on the woody biomass of forests under future climate and CO_2 concentration changes. In this study, we investigated spatial and temporal variation of stem stocking biomass and harvested biomass in China′s forests during the 21st century under different scenarios of climate and CO_2 concentration changes and management practices through combined the InTEC model with G4M model. NPP simulated from the InTEC model under three climate change scenarios were used in the G4M model, which explore the effect of forest management practices on the carbon stock of forests.

Our simulations indicated that the management targets have more influence on the time series of stem stocking biomass in China during the 21st century than climate change scenarios. CO_2 fertilization will dramatically enhance stem stocking biomass of China′s forest ecosystem under future climate regimes. If the maximum average biomass strategy is taken, stem stocking biomass of forests in China will be dramatically increasing during 2001–2100 while maximum average increment will result in an increment of stem stocking biomass before 2050 then decline. The impact of forest management on stem stocking biomass varied with forest types. Furthermore, extending the rotation length under changing climate and CO_2 concentration scenario will increase the carbon stocks of China′s forests. This could provide important implications for forest managers and policy makers to design sustainable forest management practices for China under future climate change.

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