Tellus (2007), 59B, 439–448
Printed in Singapore. All rights reserved

TELLUS

The ecosystem carbon accumulation after conversion of grasslands to pine plantations in subtropical red soil of South China

By MEI HUANG[1]*, JINJUN JI[1,2], KERANG LI[1], YUNFENG LIU[1], FENGTING YANG[1] and BO TAO[1], [1]*The Synthesis Research Center, Chinese Ecosystem Research Network, Institute of Geographical Sciences and Natural Resources Research, CAS, Beijing 100101, China;* [2]*Institute of Atmospheric Physics, CAS, Beijing 100029, China*

(Manuscript received 30 April 2006; in final form 2 February 2007)

ABSTRACT

Since 1980s, afforestation in China has led to the establishment of over 0.53×10^8 ha of new plantation forests. While this leads to rapid accumulation of carbon (C) in vegetation, the effects of afforestation on soil C are poorly understood. In this study, a new version of the Atmosphere-Vegetation Interaction Model (AVIM2) was used to examine how changes in plant C inputs following afforestation might lead to changes in soil C at one of the Chinaflux sites and to estimate the effect of afforestation on ex-grassland. The potential total C accumulation of tree plantation was also predicted. The model was calibrated by net ecosystem exchange (NEE), ecosystem respiration (RE) and gross primary production (GPP) based on eddy-covariance measurements. The simulated vegetation C and soil C stocks were compared with the filed observations.

The simulates indicate that after 22 yr of conversion of grassland to needle leaf forests (*Pinus massoniana* and *Pinus elliottii*), the net carbon accumulation in tree ecosystem was 1.96 times more than that in grassland. The soil C in the initial 7 yr of planting decreased at a rate of 0.1871 kg C m^{-2} yr^{-1}, and after that it increased at a rate of 0.090 kg C m^{-2} yr^{-1}. The C accumulation in the studied plantation ecosystem is estimated to be 76–81% of that value in equilibrium state (the net ecosystem productivity approaches to zero).

Sensitivity analyses show that conversion from grassland to plantation caused an initial (7 or 8 yr) periods of decrease in soil C stocks in wider red soil area of southern China. The soil C stocks were reduced between 19.2 and 20.4% in the initial decreasing period. After 7 or 8 yr C loss, the increased in soil C stocks was predicted to be between 0.073 and 0.074 kg C m^{-2} yr^{-1}.

1. Introduction

In general, tree plantations will increase the terrestrial C stocks and thus will mitigate anthropogenic emissions of CO_2. A better understanding of the role of tree plantations in carbon sequestration has become increasingly important since the Article 3.3 of Kyoto Protocol took afforestation as a strategy to sequester carbon. The change of carbon fluxes related to tree plantation includes two aspects, one is the increase of biomass and the other is the change of soil C stocks. The first is easy to be obtained and predicted and the later is hard to be observed, since accurate measurements of soil C often can be difficult, and measuring change in soil is likely to be problematic, arduous and taken time. A modelling approach offers the cheapest and arguably most accurate means for estimating change in soil C (Paul et al., 2003). Although the change rate of soil C is less than that of the vegetation carbon, carbon in soil organic matter makes up 80% of the terrestrial carbon pool (Bolin and Sukumar, 2000), and therefore changes in soil C may have a significant effect on the plantation carbon budget.

China has the largest tree plantation areas in the world, as detected by the national 6th forest investigation during 1999–2003, the gross tree plantation areas are 53, 257 and 300 ha (Xiao, 2005). Previous studies showed that the effect of afforestation on soil C storage depends on previous ecosystem types, climate and the type of forest established (Harmon et al., 1990; Schulze et al., 2000; Paul et al., 2002). Tree plantations established in areas where carbon stocks were previously relatively low have the potential to act as carbon sinks (Cuevas et al., 1991; Farley et al., 2004). However, the establishment of woody vegetation on

*Corresponding author.
e-mail: huangm@igsnrr.ac.cn
DOI: 10.1111/j.1600-0889.2007.00280.x

grasslands does not necessarily lead to an increase in soil C (Kaye et al., 2000; Jackson et al., 2002). Hence better understanding of the carbon sequestration in tree plantation areas is important both for scientific researches and local policy makers, especially in China with the largest tree plantation areas.

Many studies of the effects of plantations have been carried out in China before (Li, 1998; Wang and Gong, 1998; Li and Wang, 2000; Ren et al., 2000; Liu et al., 2001; Li et al., 2001; He et al., 2003; Yang et al., 2003; Song et al., 2004; Wu et al., 2004; Yu et al., 2004). Most of them were observation approaches and only associated with the change of either vegetation or soil C. There is little information on the change of both the vegetation and soil C and the net ecosystem carbon storage.

In this study, we used a process-based model to simulate the variations of vegetation and soil C in plantations in an eddy flux measurements site in southern China. The simulated gross primary production (GPP), net ecosystem exchange (NEE) and ecosystem respiration (RE) were calibrated by the data obtained by eddy flux observations. The model predicting changes in soil and vegetation carbon were also validated by observation data. By comparison the predicted vegetation and soil C stocks of tree plantation with that of nearby grassland, the effects of tree plantation on ex-grassland were estimated. By spin-up the mean climate data to the equilibrium state, the potential carbon accumulation of the plantation was also predicted by the model.

2. Methodology

2.1. Study site

This experiment site, Qian Yanzhou, is one of the 'Chinaflux' network, locating in South China subtropical monsoon climatic zone at 26°44′48″N, 115°04′13″E. Annual rainfall in the area is 1485 mm and the annual mean temperature is 17.9°C. Most areas in the same latitude zone as Qian Yanzhou around the world are arid steppes or deserts. The warm and humid environment in Qian Yanzhou is the result of unique Southeast monsoon. The original vegetation of Qian Yanzhou was most probably the evergreen broadleaf forest, but the vegetation covers have been changed much by human activities. The Qian Yanzhou ecological experimental station was established in 1983, at that time the area was mainly covered by wild grasslands, shrub lands and some sparse *Pinus massoniana*. After the experimental station setup, the land covers of Qian Yanzhou were changed much by scientists. As reported by Liu et al. (2001), the proportion areas of wild grassland decreased from 83.2% in 1983 to 5.2% in 1997 and that of forest increased from 0.88% in 1983 to 60.11% in 1997. The eddy flux observation tower was installed in the plantations (mainly consists of *Pinus massoniana* and *Pinus elliottii*) in 2001. Around tower, the forest cover reaches 90% in 1 km^2 region, and 70% in 100 km^2. The shrub under canopy mainly includes *Loropetalum chinense* and *Lyonia compta*. The soil is red soil, which weathered from red sand rock. The plantations have not been disturbed by human activities since been planted in 1983 (Li et al., 2000). The average diameter at breast (DBH), stem density and basal area for pinus massoniana in 2003 were reported to be 15.4 cm, 1300 stems h^{-1} m^{-2} and 16.92 m^2 h^{-1} m^{-2}, respectively, and those were 14.8 cm, 975 stems h^{-1} m^{-2} and 17.67 m^2 h^{-1} m^{-2} for *Pinus elliottii* (Li et al., 2006). According to the field measurements in August of 2003, the leaf area index (LAI) of the plantation was 4.5 (Li et al., 2007), and the height of the stand was 12 m (Yu et al., 2005).

2.2. Model description

The model used in the study is the Atmosphere-Vegetation Interaction Model (version2, AVIM2) that was developed for simulating seasonal and interannual variations in biophysical and biogeochemical processes at the land surface. This new version couples the original AVIM (Ji, 1995; Ji and Yu, 1999; Lu and Ji, 2006) with a dynamical soil organic matter (SOM) model. As showing in Figure 1, the AVIM2 includes a plant growth module, a soil vegetation atmosphere transfer (SVAT) scheme and a SOM module. The words in the dash line boxes in Figure 1 are the outputs of each module. While the climate, vegetation and soil variables were inputted into the SVAT module, canopy temperature and moisture were outputted to the plant growth module, and then the vegetation began to growth. The morphological characters of vegetation would be changed in growth, and then the LAI would feedback to the SVAT module. The soil temperature and moisture outputted from the SVAT module as well as the litter fall outputted from plant growth module were inputted into the SOM module, and then the heterotrophic respirations were calculated. The net ecosystem productivity would be given by using net primary productivity from plant growth module minus the heterotrophic respiration from SOM module. The original version (Ji, 1995) and modifications (Ji and Yu,

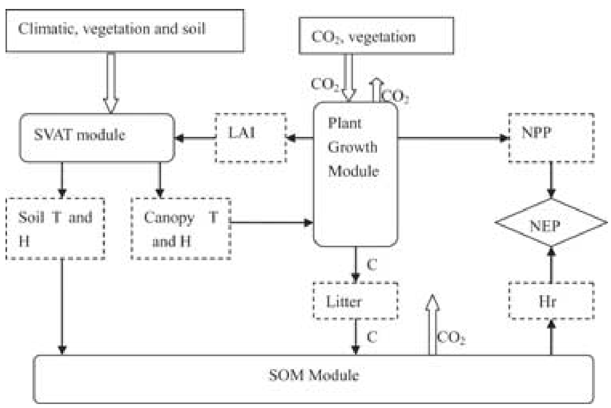

Fig. 1. The structure of the AVIM2. The contents in dash line boxes are the outputs of modules, the T, H and Hr means temperature, humidity and heterotrophic respiration, respectively.

1999; Lu and Ji, 2002; Lu and Ji, 2006) of the AVIM have been fully described before. The summary of these processes and a description of the newly developed soil organic carbon process are presented in the following sections.

2.2.1. SVAT model. The SVAT model simulates the exchange of energy, water vapour and momentum between the surface, the vegetation canopies and the atmosphere. The physical process includes solar and infrared wave radiation transfer, sensible and latent heat fluxes between air, canopy and soil, interception of rainfall and drainage, surface runoff and infiltration, evapotranspiration from the canopy and evaporation from the surface, and the snow accumulation and snowmelt processes. The details of these processes and related parameters are given by Ji and Hu (1989), Ji (1995) and Lu and Ji (2006).

2.2.2. Plant growth model. The GPP is calculated based on the well-known Farquhar model, which is based on plant physiological processes and biochemistry of photosynthesis (Farquhar et al., 1980). Numerous studies have shown that Farquhar's model can successfully estimate photosynthesis in various ecosystems over the world (Woodward et al., 1995; Haxeltine et al., 1996; Foley et al., 1996; Sellers et al., 1996; Wang and Leuning, 1998). The net primary production (NPP) is the residue of gross canopy photosynthesis minus maintenance and growth respiration. The change in biomass for the plant is determined by the budget of carbon. The allocation of assimilates among different parts in plant is based on the following presumption: At the initial stage of growing season, more carbon is allocated to foliage part, thereafter carbon allocated to root and shoot increases during the growing season. The allocation coefficients are adjusted by the seasonal LAI dynamical. For forest, the stand is divided into foliage, root and shoot. For grassland, only the separation between foliage and root part is made and the allocation coefficient for foliage part is the same as in forest. The phenological feature is assumed to be controlled by the air degree-days (above 5 °C). The offset of leaves is depended upon the life time of the leaves. The detailed description of plant growth model can be found in Lu and Ji (2006).

2.2.3. SOM model. The newly increased SOM module used an approach similar to that of Cao et al. (1998) and Parton et al. (1987). The soil organic matter was divided into eight pools: surface structural (1) and metabolic (2) litter; structural (3) and metabolic (4) root litter; surface microbe (5) and soil microbe (6); slow (7) and passive (8) carbon. The split of plant residue into metabolic (F_M) and structural (F_S) components are determined as a function of the lignin/nitrogen ratio (*L/N*), using the following equation (Parton et al., 1987):

$$F_M = 0.85 - 0.018L/N \quad (1)$$

$$F_S = 1 - F_M. \quad (2)$$

The lignin/nitrogen ratio (*L/N*) is assumed to be 40 in this study.

All carbon transformations between these pools and decomposition were considered to be first-order rate reactions and each of them had a specific decay rate coefficient (Parton et al., 1987).

$$\frac{dQ_i}{dt} = K_i f(T) f(P) Q_i, \quad (3)$$

where Q_i is the carbon in the state variable, i represents each pools; K_i is the maximum decomposition rate parameter for the ith state variable; $f(P)$ is the effect of precipitation on decomposition; and $f(T)$ is the effect of soil temperature on decomposition.

Heterotrophic respiration (HR) is determined as the sum of gaseous carbon loss in the microbial decomposition of various carbon pools:

$$\mathrm{HR} = \sum_i Q_i K_i (1 - \varepsilon), \quad (4)$$

where ε is the assimilation efficiency, that is, the fraction of decomposed carbon that is incorporated in microbial tissue (Parton et al., 1993).

Net ecosystem exchange (NEE) is the net carbon flux between ecosystems and the atmosphere and is calculated as the difference between HR and NPP.

$$\mathrm{NEE} = \mathrm{HR} - \mathrm{NPP} \quad (5)$$

The aspects for soil nitrogen inputs and outputs are the same with the CEVSA model (Cao et al., 1998). All of the expressions and functions are documented in Parton et al. (1987), Parton et al. (1993), Cao et al. (1998). However, the following modifications have been made. (1) In AVIM2 the soil was divided into four layers in vertical dimension. They are 0.1, 0.9, 1 and below 1 m from the top soil, respectively. The temperature and moisture of the first three layers change with the fluctuation of air temperature and precipitation, and the forth layer maintains a climatic mean value. The turnover and decomposition of the surface pools (structural, metabolic and microbe) were influenced by the temperature and humidity of the first layer while the other belowground pools (structural, metabolic, active, slow and passive organic) were influenced by the temperature and humidity of the other three layers. (2) The SOM module has been fully coupled to AVIM, that is daily above and below ground litters from the plant growth module were put into the SOM module in time and then the soil biogeochemical process changed with the above ground physical and physiological process timely.

2.3.4. Parameterization. The photosynthetic and soil C dynamical parameters specific for the study site are listed in Table 1. The maximum carboxylation rates for both forest and grassland are measured by on-site physiological measurements using the Licor-6400 Portable Photosynthesis System. Other parameters in this table are from other researches.

Table 1. The parameters and initial state variables used in AVIM2

Definition	Value	Units	Reference
Maximum carboxylation rate (for forest)	36	μmolm^{-2}s^{-1}	Measured
Maximum carboxylation rate (for grassland)	34	μmolm^{-2}s^{-1}	Measured
Optimal photosynthetic temperature	28	°C	Gu et al., 2006
Percents of sand	27		Yang, 2005
Percents of silt	53.2		Yang, 2005
Percents of clay	19.8		Yang, 2005
Soil N:C	0.063		Gu et al., 2006
Saturated soil water content	0.42	cm^{3}cm^{-3}	Gu et al., 2006
Soil moisture at Wilt point	0.12	cm^3 cm^{-3}	Gu et al., 2006
Soil moisture at field capacity	0.25	cm^3 cm^{-3}	Gu et al., 2006
Initial soil C	6.82	kg C m^{-2}	Yang, 2005

2.3. Experiment design

This experiment aims at estimating the change of ecosystem carbon stocks after conversion of wild grasslands to tree plantation in the red hilly area of southern China, and predicting the potential carbon accumulation of the plantation. The simulations were conducted by following steps:

1. Simulating the vegetation and the soil C densities of the wild grassland in the period of 1983–2004. The observed soil C stocks of 1983 were taken as the initial soil C state variable, and the observed grassland vegetation carbon was used to validate the model. Since long term meteorological data is not available in Qian Yanzhou, the meteorological data of a nearby meteorological station which is located at 26°48′N, 114°55′E, less then 10 km away from the study site, were used to run the model from 1983 to 2004.
2. Simulating the carbon fluxes change of tree plantation in the period of 1983–2004. We used the meteorological data of 1983–2004 to simulate the carbon fluxes of the tree plantation and used the NEE, RE and GPP obtained from eddy covariance measurements to calibrate the model. The soil C pools of grasslands in 1983 were used as the initial input to the model. The predicted biomass and soil C stocks were also compared with the field observations.
3. Estimating the maximum vegetation and soil C stocks of the plantation. We assumed that the tree plantation in equilibrium state gets its maximum C stocks. The equilibrium C stock is the result of a balance between inflows and outflows to the ecosystem carbon pool. In this study, equilibrium means that all state variables of the model must change of less than few percent from the year to another and the heterotrophic respiration (RH) almost equals NPP. The meteorological data used for loop running is the data of 1962 because of its annual mean temperature and precipitation are mostly closed to the mean values of 1962–2004. Statistical analyses show that the standard deviation of annual mean temperature and the variation of precipitation for Qian yanzhou is 0.376 °C and 21.4%, respectively. So both the temperature and precipitation were varied (i.e. temperature by plus or minus 0.376 °C and the precipitation by plus or minus 21.4%) to get the maximum and minimum C stocks in equilibrium state. The maximum and minimum C stocks in equilibrium are taken as the span for the equilibrium state C estimation.

2.4. Model validation

The model for tree plantation modeling was validated by the data obtained from eddy-covariance based measurements (Yu et al., 2005; Liu et al., 2006). The ecosystem respiration model used for getting the GPP estimations from eddy-covariance data in the study site is Q_{10} model. In the Q_{10} model, RE is described with Van's Hoff function.

$$\mathrm{RE} = \mathrm{RE}_{\mathrm{ref}} e^{\ln(Q_{10})(T_k - T_{\mathrm{ref}})/10}, \tag{6}$$

where $\mathrm{RE}_{\mathrm{ref}}$ is the ecosystem respiration at the reference temperature (T_{ref}); T_k is air temperature. The Q_{10} is related to temperature and soil water content which could be described with quadratic equation.

$$Q_{10} = a - bT_k + cS_w + dS_w^2, \tag{7}$$

where, a, b, c and d are site-specific parameters, in which $b > 0$ and $d \leq 0$. S_w is surface soil water content. Details of the related assumptions and measurements were full described in Yu et al. (2005) and Liu et al. (2006).

We compared measured and modelled daily carbon exchange in 10 d periods to examine model output. Figure 2 shows comparisons of means for 73 10-d periods in 2003 and 2004. The simulated GPP are closed to the measurements (Fig. 2a, $y = 0.228 + 0.995x$, $r^2 = 0.82$). We also found a closed correlation between simulated and measured RE (Fig. 2b, $y = 0.054 + 0.985x$, $r^2 = 0.84$). There was a drought occurred in the area during June and

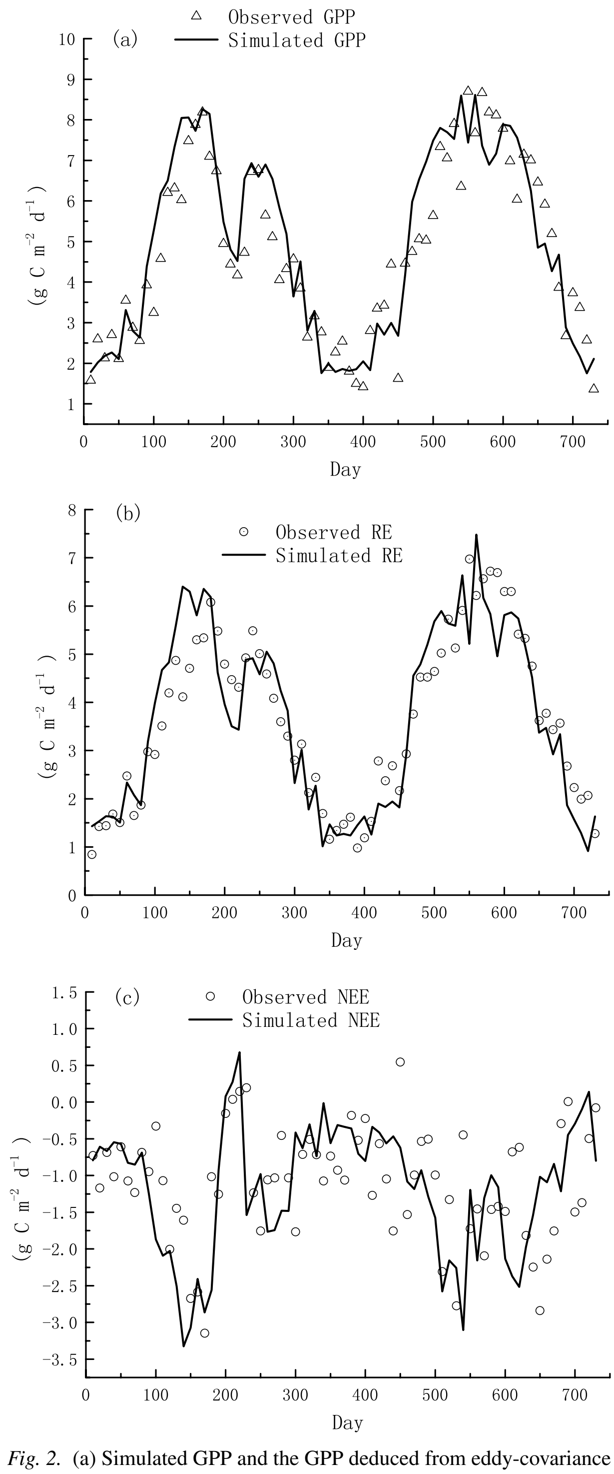

Fig. 2. (a) Simulated GPP and the GPP deduced from eddy-covariance based measurements in ten days period mean; (b) Simulated RE and the RE deduced from eddy-covariance based measurements in ten days period mean; (c) Simulated vs. observed daily NEE in 10-d period mean. The value in the abscissa axis is days from January 1, 2003. The source of eddy-covariance based measurements is from Liu et al. (2006).

July in 2003. The precipitation of the year was 945 mm which was only 69% of the average value. From Figure 2 we can see that both simulation and eddy-covariance based measurements could reflect the influence of drought in growth season in 2003. There were more scatter in predicted vs. observed 10 days mean NEE resulting from errors in estimates of the GPP and NEE (Fig. 2c).

In sever drought year of 2003, the observed vs. predicted daily NEE mean is -1.087 and -1.161 g C m^{-2}, respectively. The predicted daily NEE is a little higher than the observed NEE in 2003. However, in the normal year of 2004, the observed daily NEE mean, which is -1.182 g C m^{-2}, is much closer to the predicted NEE (-1.183 g C m^{-2}). This suggested that the AVIM2 could generally predict the seasonal and interannual carbon fluxes well in the tree plantation of the area.

3. Results

3.1. Estimated vegetation and soil carbon of wild grassland

Simulated soil C stocks within 1m depth under wild grassland varied from 6.857 to 6.792 kg C m^{-2}, with the average of 6.830 kg C m^{-2} and the standard deviation of 0.0189 (Fig. 3a). Since the grassland biomass has great seasonal change, the curve displayed in Figure 3b is yearly average vegetation carbon. The simulated grassland biomass is agreed with the field observation in 1998. The vegetation carbon observation was obtained by quadrat method (Li, 2001). Simulated total grassland vegetation varied from 0.606 to 0.562 kg C m^{-2}, with the average of 0.589 kg C m^{-2} and the standard deviation of 0.012. From the standard deviations of the soil and vegetation carbon we could found that in this area the mean soil and vegetation carbon variations caused by inter annual variability of climate are only 1.89 and 1.2%, respectively.

3.2. Comparison of predicted vegetation and soil carbon stocks of tree plantation with field data

In Figure 4, the predicted tree vegetation carbon and soil C stocks within 1 m are compared with observed vegetation carbon of *Pinus massoniana* and *Pinus elliottii* and the soil C stocks under them. The biomass observation data was obtained by biomass harvest method, except for the data of 2003, which was obtained by a growth equation in which the shoot biomass was the function of mean DBH and mean stem density, and the root biomass was estimated as 20% of the total biomass (Yang, 2005).

The simulated vegetation and soil C are generally agreed with the observations of *Pinus elliottii* and a little higher than the observation of *Pinus massoniana* (Fig. 4a). As shown in Figure 4b, in the first 7 yr of planting, the soil C stocks decreased from 6.82 to 5.51 kg C m^{-2}, and the average decreasing rate was 0.187 kg C m^{-2} a^{-1}. The soil C stock has been increased since 1991, and

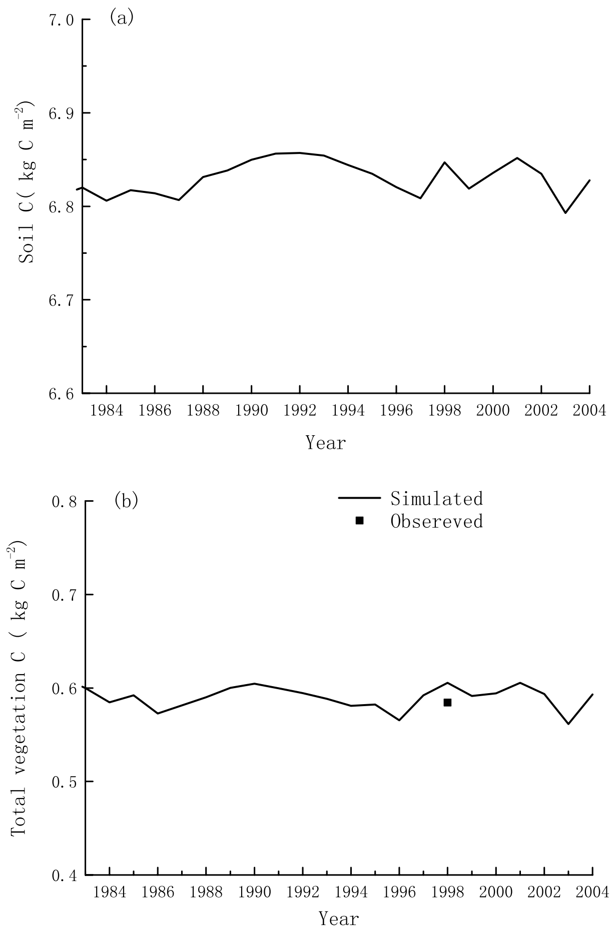

Fig. 3. (a) Simulated soil C stocks within 1m depth under wild grassland and (b) Simulated and observed wild grassland vegetation C. Observation data source: Li et al. (2001).

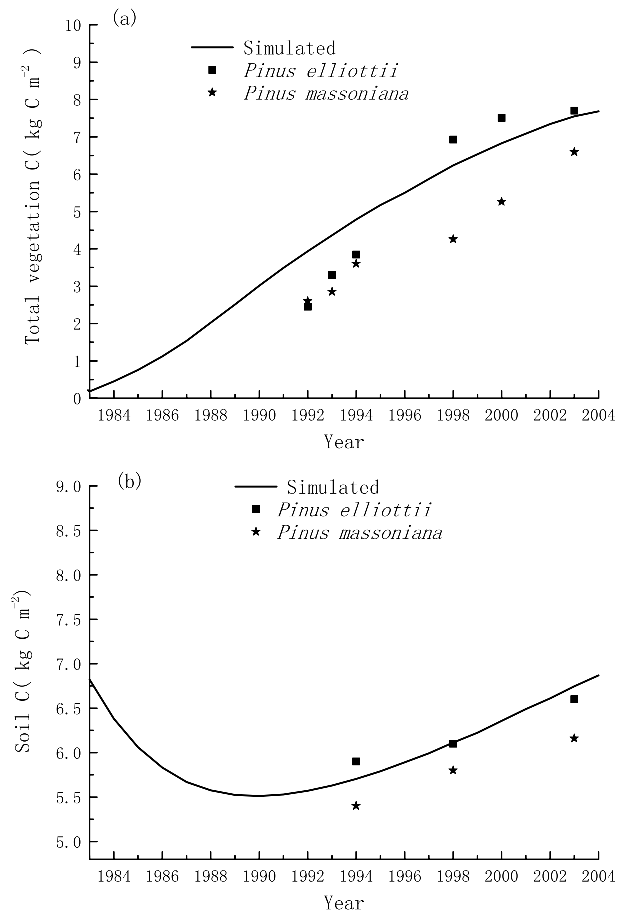

Fig. 4. (a) Comparison of predicted plantation vegetation C with field observations; (b) Simulated soil C stocks (within 1m depth) under the plantation vs. filed measurements. Observation data source: Yang (2005).

the average increase rate was 0.090 kg C m^{-2} a^{-1}. In 2004, the soil C stocks reached 6.86 kg C m^{-2}, and the total vegetation carbon reached 7.63 kg C m^{-2}.

3.3. *The predicted carbon sequestration of the tree plantation in equilibrium state*

The NPP, vegetation carbon and the soil C stocks within 1m depths in equilibrium state and there variation range for tree plantation were shown in Table 2. In equilibrium state, the predicted NPP is 0.68 kg C m^{-2} a^{-1}, and its variation range is 0.674–0.689 kg C m^{-2} a^{-1}. This simulation is a little higher than the estimation of Ni (1996) (0.61 kg C m^{-2}) and lower than the estimation of Zhou et al. (1998) (0.729 kg C m^{-2}) for this area.

Simulated mean vegetation carbon is 9.51 kg C m^{-2} in equilibrium state, and the span of prediction is 9.25–9.89 kg C m^{-2}. According to the forest inventory of China (Zhao and Zhou, 2005), the stand biomass of *pinus massoniana* near this study area ranged from 32 to 202.6 Mgha^{-1}. If we use the coefficient of 0.45 to change the stand biomass to carbon density and add 20% for root biomass, that number will be 1.8 and 11.4 kg C m^{-2}. The simulated vegetation carbon density is in the range of the investigated value.

Table 2. Simulated NPP, vegetation and soil C of tree plantation in equilibrium state at Qian Yanzhou

	NPP (kg C m^{-2} a^{-1})	Vegetation C (kg C m^{-2})	Soil C (kg C m^{-2})
Predicted	0.680	9.510	8.640
variation range	0.674–0.689	9.25–9.89	8.16–9.02

The soil C estimated in equilibrium state is 8.64 kg C m^{-2}, and its variation is 8.16–9.02 kg C m^{-2}. This simulation is close to the estimate of Xie et al., 2004 (8.95 kg C m^{-2}) and Li et al., 2001 (8.46 ± 2.37 kg C m^{-2}) for red soil in China.

In conclusion, as compared with other researches, the simulated NPP, vegetation and soil C in equilibrium state for Qian

Yanzhou was in a reasonable range. The predicted net ecosystem C accumulation in equilibrium state was 18.83 kg C m^{-2}, its variation ranged form 18.06 to 19.60 kg C m^{-2}.

3.4. Comparison of predicted and field measured LAI

Modeled LAI was compared with field measurements at the site in September and November of 2004 (Fig. 5a). The result shows that the simulated LAI agreed well with the measurements though the measurements were only taken in two months. The LAI was measured using the tracing radiation and architecture of canopies (TRAC), which is an optical instrument for measuring the LAI and the fraction of photosynthetically active radiation absorbed by plant canopies (FPAR). The LAI features strong seasonal patterns with lowest LAI appeared in April and highest in August. In addition, the LAI increased rapidly from April to August and then it declined continuously to the next minimum (Fig. 5a). The multiyear LAI dynamics were validated against field measurements at only one time in 2003. The LAI increased rapidly from 0.6 in 1983 to 4.55 in 2004. It is noted that the decline of LAI in 2003 was probably due to the sever summer drought in 2003. The modeled LAI is very close to the measured LAI (Li et al., 2007), suggesting the model can well simulate the drought effect on LAI dynamics (Fig. 5b).

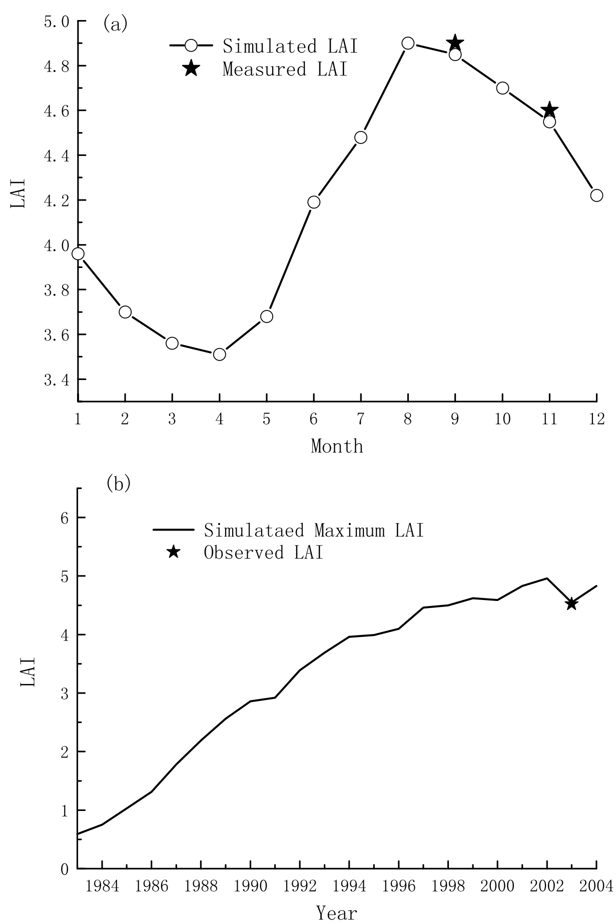

Fig. 5. (a) Simulated monthly mean LAI of 2004 vs. the LAI measurements for September and November and (b) inter annual changes of simulated maximum LAI vs. LAI measurements for *Pinus elliottii* in August of 2003. The source of observation is from Li et al. (2007).

4. Discussion

4.1. The effect of tree plantation on soil carbon stocks

Although there is much inconsistent in the researches of change in soil C following afforestation, many studies observed an initial decrease in soil C after afforestation (Grigal and Berguson 1998; Turner and Lambert, 2000; Paul et al., 2002) which is consistent with this study. The amount of carbon stored in the soil is the balance between inputs of organic material from the biota and the losses primarily through soil respiration. Within the first several years of afforestation, there will be relatively little input of carbon from aboveground due to a small forest biomass and low rate of litterfall. So the simulated soil C trend is reasonable.

In this study, soil C decreased 19.2% in the first 7 yr of planting. By referencing global 83 cases of pasture conversed to plantation, Guo and Gifford (2002) reported that the change rates of the soil C after conversion of pasture to plantation were related to annual precipitation of the study area. The conversion had little effect on soil C stocks in areas with annual precipitation less than 1200 mm. However, in the area with higher precipitation especially the annual precipitation greater than 1500 mm, the soil C will decrease about 23%. The annual precipitation of Qian Yanzhou is 1404 mm, the change rate of the soil C in Qian yanzhou is close to the global mean.

4.2. The effect of tree plantation on ecosystem net carbon accumulation and the potential carbon sequestration of the tree plantation

The simulated vegetation and soil C for grassland did not shown significant changing trend during the period of 1983–2004, but those in tree plantation changed rapidly. In 2004, the simulated soil C under tree plantation is 6.8681 kg C m^{-2}, and the vegetation C is 7.6814 kg C m^{-2}. Both vegetation and soil C in plantation exceed those in grassland. The simulated vegetation C and soil C stock under grassland in 2004 is 6.8278 and 0.5932 kg C m^{-2}, respectively.

The net carbon accumulation in plantation is 14.55 kg C m^{-2} which is 1.96 times of the grassland. The predicted mean net C accumulation for tree plantation in equilibrium state is 18.83 kg C m^{-2}, ranged from 18.06 to 19.60 kg C m^{-2}. If we take the C accumulation in equilibrium as the saturated C accumulation value in the study area, then the net C accumulation in the 22 yr stand is predicted to be 76–81% of the saturated value.

Table 3. The influence of the temperature and precipitation change on the soil C stocks

$T = 17.9$ °C, $P = 1485$ mm	Initial decrease time period (yr)	Decrease percent (%)	Average decreasing rate (kg C $m^{-2}a^{-1}$)	Average increasing rate (kg C $m^{-2}a^{-1}$)
T, P	7	19.2	0.187	0.090
T +2 °C, P	7	20.3	0.197	0.081
T −2 °C, P	7	18.4	0.179	0.095
$T, P-32\%P$	8	19.2	0.165	0.073
$T, P+7.7\%P$	7	19.3	0.187	0.094
T +2 °C, $P+7.7\%P$	7	20.4	0.198	0.086
T −2°C, $P-32\%P$	8	18.4	0.158	0.077

4.3. The sensitivity of the soil carbon change to precipitation and temperature

The similar red soil plantations like Qianyanzhou are broadly distributed in Jiangxi, Hunan, Hubei, Zhejiang, Guangdong and Fujian Provinces in southern China (Liu et al., 2001; Li et al., 2001). In these areas, the annual mean temperature ranges from 16 to 20°C, and the precipitation ranges from 1000 to 1600 mm, and the higher precipitation always accompanied by higher temperature. As we introduced before, the rainfall in Qian Yanzhou was 1485 mm and the annual mean temperature was 17.9 °C, so we changed the temperature and precipitation in the range of the area (i.e. daily temperature were varied by plus or minus 2 °C, and the precipitation by plus 7.7% or minus 32%) to see how the temperature and precipitation change in the red soil area will influence the soil C change result (Table 3).

Table 3 shows that the temperature change did not influence the soil C initial decrease time period (7 yr), but it did influence the soil C change rate. The temperature rise was predicted to accelerate the initial soil C loss rate (0.197 kg C $m^{-2}a^{-1}$), and slow down its recovering rate (0.081 kg C $m^{-2}a^{-1}$), while the temperature drop was predicted to slow down the soil C decreasing rate (0.179 kg C $m^{-2}a^{-1}$), and accelerate its increasing rate (0.095 kg C $m^{-2}a^{-1}$). In higher temperature case, more soil C stocks were decreased by (20.3%) than in lower temperature case (18.4%). The lower precipitation ($P = 1000$ mm) was predicted to increase the initial soil C loss time period to 8 yr, and slow down both the soil C loss and recovering rate. However, not led to the initial soil C stocks change percent (19.2%). The higher precipitation ($P = 1600$ mm) did not predicted to change the initial soil C decrease time period and initial decreasing rate but to accelerate the increasing rate, and led to a little more soil C stocks loss (19.3%). In the area with higher temperature and higher precipitation ($T = 19.9$ °C, $P = 1600$ mm), the initial soil C decrease time period (7 yr) is not changed, but the initial soil C loss rate is predicted to be accelerated (0.198 kg C $m^{-2}a^{-1}$) and the soil C recovering rate to be slow down (0.086 kg C $m^{-2}a^{-1}$), and the initial soil C stocks were reduced by 20.4%. However, in the area with lower temperature and lower precipitation ($T = 15.9$ °C, $P = 1000$ mm), the initial soil C decrease time period is predicted to be 8 yr, and both the soil C increasing and decreasing rate are predicted to be slow down, and the initial soil C stocks were predicted to be reduced by 20.4%.

In conclusion, conversion from grassland to plantation in the red soil area in southern China was predicted to cause an initial (7 or 8 yr) periods of decrease in soil C stocks was of between 0.158 and 0.198 kg C m^{-2} yr^{-1}. The soil C stocks were reduced by 19.2–20.4%. After 7 or 8 yr, it was predicted that the increased in soil C stocks to be between 0.073 and 0.074 kg C m^{-2} yr^{-1}. In the study area, the effect of temperature on soil C change is more significant than that of precipitation. It is predicted that higher temperature caused more carbon loss and less soil C recovering rate than lower temperature did.

5. Acknowledgments

The present paper was supported by the following projects: National Nature Science Important Project 30590384 ‘The Synthesis analysis of the response and acclimation of the function and structure of regional ecosystem to global change’; State key basic research development and planning project CB412500 ‘Terrestrial ecosystem carbon cycle model study’. Special thanks go to Dr. Ming Xu who helped with the revision of this manuscript.

References

Baldocchi, D. D. 1994. An analytical solution for coupled leaf photosynthesis and stomatal conductance models. *Tree Physiol.* **14**, 1069–1079.

Bolin, B. and Sukumar, R. 2000. Global perspective. In: *Land Use, Land-Use Change, and Forestry. A Special Report of the IPCC* (eds.R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken). Cambridge Univ. Press, Cambridge, pp. 23–51.

Cao, M. and Woodward, F. I., 1998. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biol.* **4**, 185–198.

Cuevas, E., Brown, S. and Lugo, A. E., 1991. Above and belowground organic matter storage and production in a tropical pine plantation and a paired broadleaf secondary forest. *Plant Soil* **135**, 257–68.

Farquhar, G. D., Caemmerer, S. and Berry, J. A., 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 plants. *Planta* **149**, 78–90.

Farley, K. A., Kelly, E. F. and Hofstede, R. G. M., 2004. Soil organic carbon and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes. *Ecosystems* **7**, 729–739.

Foley, J. A., Prentice, I. C., Ramankutty, N., Levis, S., Pollard, D. and co-authors. 1996. An integrated biosphere model of land surface process, terrestrial carbon balance and vegetation dynamics. *Global Biogeochem. Cycles* **10**, 603–628.

Grigal, D. F. and Berguson, W. E., 1998. Soil carbon changes associated with short-rotation systems. *Biol. Bioeng.* **14**(4), 371–377.

Gu, F. X., Cao, M. K., Wen, X. F., Liu, Y. F. and Tao, B. 2006. A comparison between simulated and measured CO_2 and water flux in a sub-tropical coniferous forest. *Sci. China Ser. D* **49**(Suppl. II), 241–251.

Guo, L. B. and Gifford, R. M. 2002. Soil carbon stocks and land use change: a meta analysis. *Global Change Biol.* **8**, 345–360.

Harmon, M. E., Ferrell, W. K. and Franklin, J. F. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* **247**, 699–702.

Haxeltine, A. and Prentice, I. C. 1996. BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles* **10**(4), 693–709.

He, Y. Q., Shen, Q. R. and Wang, X. X., 2003. Dynamic of nutrients in artificial forest soil in low hill red soil region (In Chinese). *Soils* **35**(3), 222–226.

Jackson, R. B., Banner, J. L., Jobba´gy, E. G., Pockman, W. T. and Walls, D. H. 2002. Ecosystem carbon loss with woody plant invasion of grasslands. *Nature* **418**, 623–626.

Ji, J. J. and Hu, Y. 1989. A simple land surface process model for use in climate study. *Acta Meteorol. Sin.* **3**, 344–353.

Ji, J. J. and Yu, L. 1999. A simulation study of coupled feedback mechanism between physical and biogeochemical processes at the surface (In Chinese). *Chin. J. Atmos. Sci.* **23**(4), 439–448.

Ji, J. J., 1995. A climate-vegetation interaction model: simulating physical and biological processes at the surface. *J. Biogeogr.* **22**, 2063–2069.

Kaye, J. P., Resh, S. C., Kaye, M. W. and Chimner, R. A. 2000. Nutrient and carbon dynamics in a replacement series of Eucalyptus and Albizia trees. *Ecology* **81**(12), 3267–273.

Li, X. R., Liu, Q. J., Cai, Z. and Ma, Z. Q. 2006. Leaf area index measurement of *Pinus elliotii* plantation (In Chinese). *Acta Ecol. Sin.* **26**(12), 4099–4105.

Li, L. H., 1998. Effects of land-use change on soil carbon storage in grassland ecosystems (In Chinese). *Acta Phytoecol. Sin.* **22**(4), 300–302.

Li, X. R., Liu, Q. J., Chen, Y. R., Hu, L. L. and Yang, F. T. 2006. Above-ground biomass of three conifers in Qianyanzhou plantation (In Chinese). *Chin. J. Appl. Ecol.* **17**(8), 1382–1388.

Li, Z. P. and Wang, X. J., 2000. Analysis and devaluation of soil organic matter dynamics at a little region scale (In Chinese). *Sci. Geograph. Sin.* **20**(2), 45–50.

Li, Z., Sun, B. and Zhao, Q. G., 2001. Density and storage of soil organic carbon in East China (In Chinese). *Agro-Environ. Protection* **20**(6), 385–389.

Liu, Y. F., Li, J. Y., Chen, Y. R. and Lin, Y. M., 2001. The effect of afforestation on vegetation and soil moisture (In Chinese). *J. Nat. Resour.* **16**(5), 457–460.

Liu, Y. F., Yu, G. R., Wen, X. F. and co-authors, 2006. Seasonal dynamics of CO_2 fluxes from sub-tropical plantation coniferous ecosystem. *Sci. China Ser. D* **49**(Suppl. II), 99–109.

Lu, J. and Ji, J. 2002. A simulation study of atmosphere-vegetation interactions over the Tibetan Plateau. Part I Physical fluxes and parameters (In Chinese). *Chin. J. Atmos. Sci.* **26**(1), 111–126.

Lu, J. and Ji, J. 2006. A simulation and mechanism analysis of long-term variations at land surface over arid/semi-arid area in north China. *J. Geophys. Res.* **111**(d9): D09306, 1–19.

Ni, J. 1996. Estimate of the net primary productivity for subtropical evergreen broadleaved forest in China (In Chinese). *Chin. J. Ecol.* **15**(6), 1–8.

Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, D. S., 1987. Division S-3-soil microbiology and biochemistry, Analysis of factors controlling soil organic matter levels in great plains grasslands. *Soil Sci. Soc. Am. J.* **51**, 1173–1179.

Parton, W. J., Scurlock, J. M. O., Ojima, D. S. and co-authors, 1993. Observations and modelling of biomassand soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochem. Cycles* **7**, 785–809.

Paul, K. I., Polglase, P. J. and Richards, G. P., 2003. Sensitivity analysis of predicted change in soil carbon following afforestation. *Ecol. Model.* **164**, 137–152.

Paul, K. I., Polglase, P. J., Nyakuengama, J. G. and Khanna, P. K., 2002. Change in soil carbon following afforestation. *Forest Ecol. Manag.* **168**, 241–257.

Ren, H., Peng, S. L. and Xiang, Y. C., 2000. Biomass and net primary productivity in an *acacia mangium* plantation in Heshan, Guangdong, China. *Acta Phytoecol. Sin.* **24**(1), 18–21.

Schulze, E., Wirth, C. and Heimann, M. 2000. Managing forests after Kyoto. *Science* **289**, 2058–2059.

Sellers, P. J., Randall, D. A., Collatz, G. J. and co-authors, 1996. A revised land surface parameterization (SIB2) for atmospheric GCMs. Part 1. Model formulation. *J. Climate* **9**, 676–705.

Song, X., Liu, Y. F., Xu, X. F., Yu, G. R. and Wen, X. F. 2004. Comparison study on carbon dioxide, water and heat fluxes of the forest ecosystem in red earth hilly zone over winter and spring (In Chinese). *Resour. Sci.* **26**(3), 96–104.

Turner, J. and Lambert, M. 2000. Change in organic carbon in forest plantation soils in eastern Australia. *For. Ecol. Mgmt.* **133**, 231–247.

Wang, X. J. and Gong, Z. 1998. Assessment and prediction of soil changes under different land use patterns at a small area level in red soil hilly region (In Chinese). *Acta Pedologica Sinica* **35**(1), 135–139.

Wang, Y.-P. and Leuning, R. 1998. A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I: model description and comparison with a multi-layered model.Agric. *For. Meteorol.* **91**, 89–111.

Woodward, F. I., Smith, T. M. and Emanuel, W. R. 1995. A global land primary productivity and phytogeography. *Global Biogeochem. Cycles* **9**(4), 471–490.

Wu, J. G., Zhang, X. Q. and Xu, D. Y., 2004. Impact of land use change on soil carbon storage (In Chinese). *Chin. J. Appl. Ecol.* **15**(4), 593–599.

Xiao, X. W. (ed.), 2005. *Atlas of Forest Resources of China*. China Forestry Press, Beijing.

Xie, X. L., Sun, B., Zhou, H., Li, Z. P. and Li, A. 2004. Organic carbon density and storage in soils of China and spatial analysis (In Chinese). *Acta Pedologica Sinca.* **41**(1), 35–43.

Yang, F. T., 2005. *The effect of land-use change on the terrestrial carbon cycle: an example of Qian Yanzhou red earth hilly area.* PhD Dissertation. Chinese Academy of Sciences, Beijing, CN.

Yang, J. C., Han, X. G., Huang, J. H. and Pan, Q. M., 2003. Effects of land use change on carbon storage in terrestrial ecosystem. *Chin. J. Appl. Ecol.* **14**(8), 1385–1390.

Yu, G., Wen, X., Li, Q., Zhang, L., Ren, C. and co-authors. 2005. Seasonal patterns and environmental control of ecosystem respiration in subtropical and temperate forests in China. *Sci. China, Ser. D* **48**(Suppl.), 93–105.

Yu, Z. Y., Yang, Y. S. and Chen, G. H., 2004. Changes of carbon storage and carbon sequestration in plantation ecosystems on purple soil (In Chinese). *Chin. J. Appl. Ecol.* **15**(10), 1837–1841.

Zhao, M. and Zhou, G. S., 2005. Estimation of biomass and net primary productivity of major planted forests in China based on forest inventory data. *Forest Ecol. Manage.* **207**, 295–313.

Zhou, G. S., Zheng, Y. R., Chen, S. Q. and Luo, T. X., 1998. NPP model of natural vegetation and its application in China (In Chinese). *Scientia Silvae Sinicae* **34**(5), 1–11.