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Observation and modeling of NPP for *Pinus elliottii* plantation in subtropical China

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Based on the stem analysis of 59 individuals of *Pinus elliottii* in combination with tree biomass models, we calculated annual biomass increment of forest plots at Qianyanzhou Ecological Station, Chinese Academy of Sciences in subtropical China. In addition, canopy layer and community NPP were calculated based on 12 years' litter fall data. NPP of the 21-year-old forest was estimated by using the BIOME BGC model; and both measured NPP and estimated NPP were compared with flux data. Community biomass was 10574 g·m^{-2}; its distribution patterns in tree layer, shrub layer, herbaceous layer, tree root, herbaceous and shrub roots and fine roots were 7542, 480, 239, 1810, 230, 274 and 239 g·m^{-2}, respectively. From 1999 to 2004, the average annual growth rate and litter fall were 741 g·m^{-2}·a^{-1} (381.31 gC·m^{-2}·a^{-1}) and 849 g·m^{-2}·a^{-1} (463 gC·m^{-2}·a^{-1}), respectively. There was a significant correlation between annual litter fall and annual biomass increment; and the litter fall was 1.19 times the biomass increment of living trees. From 1985 to 2005, average NPP and GPP values based on BGC modeling were 630.88 (343.31—906.42 gC·m^{-2}·a^{-1}) and 1 800 gC·m^{-2}·a^{-1} (1351.62—2318.26 gC·m^{-2}·a^{-1}). Regression analysis showed a linear relationship (R^2=0.48) between the measured and simulated tree layer NPP values. NPP accounted for 30.2% (25.6%—32.9%) of GPP, while NEP accounted for 57.5% (48.1%—66.5%) of tree-layer NPP and 41.74% (37%—52%) of stand NPP. Soil respiration accounted for 77.0% of measured tree NPP and 55.9% of the measured stand NPP. NEE based on eddy covariance method was 12.97% higher than the observed NEP.

NPP, BGC, litter, annual biomass increment, flux

Net primary productivity (NPP) is an important indicator of energy flow and nutrient exchange in ecosystems. It supports nearly all heterotrophy (organisms that require preformed organic compounds for food) on the earth, including human beings[1]. Vitousek et al.[2] estimated that 40% of NPP is consumed by human. Accurately estimating net primary productivity is critical to understand carbon dynamics within the atmosphere-vegetation-soil continuum and the response of terrestrial ecosystem to potential climate warming[3]. The main research methods on NPP are small-scale field investigations and macro-scale simulations. Most previous studies were conducted with dimension analysis, stem analysis and flux measurement methods[4−6]. Regional NPP was mainly estimated by using the statistical models, process models and parametric models. Process models, with complete theoretical bases, could be applied to interpreting biological and biophysical mechanisms of plants[7], such as TEM[8], BGC[9,10] and

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BEPS[11]. Individual plant biomass could be estimated using relative growth models. However, underground biomass, especially for fine roots, is often neglected[12]. It is difficult to accurately measure biomass in both canopy layer and substratum[13]; and biomass values are often underestimated[14].

At present, flux measurement by eddy covariance method is considered a powerful means for studying the mechanism of CO_2 exchange between the atmosphere and ecosystems[4,5]. However, it is cost-intensive and is not necessarily as accurate as conventional approaches for biomass and soil carbon content, especially for sites with uneven topography[15]. For relatively short time scales, the net ecosystem production (NEP) is approximately equivalent to net ecosystem exchange (NEE)[16]. Comparative studies between NEP and NEE are useful to accurately estimate forest ecosystem carbon storage and to understand the causes of variation in annual carbon sequestration within and among sites[17]. In this study, we conducted an analysis by comparing data from field investigations with 3-a flux measurement results[6,18].

Biome-BGC1) is a widely used bio-geochemical model, which simulates the storage and dynamics of energy, water, carbon and nitrogen within vegetation and soil in terrestrial ecosystems. It is developed from a forest BGC model, which primarily describes forest carbon and nitrogen cycling[9, 10]. The BEPS[11] model also follows the principles of the BGC model. BGC is appropriate for simulation of NPP in artificial forest.

The estimation accuracy of models can be significantly affected by many factors, such as scaling up[19], data acquisition and data quality[3]. Accurate and reliable data are essential for validating outputs derived by remote sensing. Uncertainty of forest NPP estimation is mainly introduced by three factors: sampling scheme, measuring method and calculating algorithms[20]. Partly because of this, the mechanism of carbon sink in forest ecosystem has not been satisfactorily clarified[21]. A potential breakthrough may rely on multi-scale observation and trans-scale modeling, e.g. quantitative simulation, helping us to understand the interactions between carbon cycling and ecosystem processes at different scales[15]. To accurately estimate NPP, it is essential to integrate multi-source data with long-term experiments.

In the early 1980s, slash pine (*Pinus elliottii*) was widely planted in south China to help preventing the severe degradation of ecosystems due to soil and water erosion. In terms of ecological restoration, it is significant to evaluate the contribution of the afforestation to environmental improvement on the basis of productivity, which is practical for ecosystem management and regional sustainable development. NPP can be measured through field survey, modeling simulation, as well as direct non-destructive measurement (eddy covariance method). Integrating different approaches could derive regional patterns of ecosystem productivity more precisely.

In this study, NPP of the slash pine plantation was measured and estimated at various scales, from individual trees to population, community and small watershed. The test site is located in Qianyanzhou Ecological Station in subtropical China. NPP calculated by Biome BGC model was compared with NEE by eddy covariance method. The DBH regression models were fitted by stem analysis with 59 trees and the annual net increment of community biomass was evaluated by field survey including the understory component. 12-year continuous measurement data on litter fall were also used for this study. The NPP of slash pine plantation from 1985 to 2005 in Qianyanzhou was simulated by BGC 4.2[22] based on meteorological information and local tested parameters. A comparison among the results from the three approaches is carried on and the possible limitation for each method is discussed.

1 Study site and methods

1.1 Site description

Qianyanzhou Ecological Station, Chinese Academy of Sciences, is located in the red earth hilly area in Taihe County, Jiangxi Province (26°44′N, 115°04′E). The total experimental area is 212.13 hm^2, where coniferous forest covers about 70%. The elevation is about 100 m. The monsoon climate dominates in this region. The mean annual temperature is 17.9℃ and annual precipitation is 1489 mm. The clear-sky duration per year is 1306 h and the solar radiation is 4349 $MJ \cdot m^{-2}$. The soil is typical red earth, which is predominant in the entire subtropical region. The most common parent materials are red sandstone, sandy conglomerate, mudstone and alluvium[23].

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1) Biome-BGC Version 4.1.2 was provided by Peter Thornton at the National Center for Atmospheric Research (NCAR), and by the Numerical Terra Dynamic Simulation Group (NTSG) at the University of Montana. NCAR is sponsored by the National Science Foundation.

The forest plantation began in 1985, including slash pine (*Pinus elliottii*) forest, *Cunninghamia lanceolata* forest, *Pinus massoniana* forest, *Schima superba* forest, *Liquidambar formosana* forest and *Cirtus reticulata* orchard. Dominant shrubs are *Quercus fabri*, *Loropetalum chinense* and *Lespedeza formosa*. Herbaceous species are mainly dominated by *Arundinella setosa* and *Helicteres angustifolia*. With canopy closure, shade-tolerant ferns are increasingly present, such as *Adiantum flabellulatum*, *Blechnum oriental*, *Woodwardia japonica* and *Dryopteris championi*[24].

1.2 Methods

(1) Forest biomass survey. Twenty-nine slash pine forest plots, with an area no less than 20 m × 20 m, were investigated from July to September 2005. DBH of all trees was measured. Based on stem analysis, the relative growth models of biomass established previously[25] are shown in Table 1. Root biomass of the canopy layer was measured by weighing all primary and lateral roots using 5 samples. The ratio between aboveground and underground biomass of trees was calculated; and the underground biomass was estimated based on this ratio.

Table 1 Biomass models for individual trees of *P. elliottii* at Qianyanzhou

Items	Biomass models	R^2	N
Leaves	$W_{\text{leaves}}=12.0741D^{2.1515}$	0.735	19
Branches	$W_{\text{branches}}=40.1892D^{2.0074}$	0.713	19
Stems	$W_{\text{stems}}=24.88D^{2.5459}$	0.991	19
Above ground	$W_{\text{above biomass}}=54.0477D^{2.4295}$	0.959	19
Roots	$W_{\text{roots}}= 0.239W_{\text{above-ground biomass}}$		5

(2) NPP observation for canopy layer. NPP of trees was directly measured in December 2004 by destructive harvesting. A total of 59 slash pines (mean DBH: 17.35 cm) were analyzed with sliced discs.

Since the input parameter, DBH, for relative growth model must be with bark, a regression model ($\text{DBH}_{\text{\_over bark}} = -0.043 + 1.22\ DBH_{\text{\_in bark}},\ R^2 = 0.99$) was fitted to estimate the over-bark DBH in the past years. NPP of the entire community, including shrubs, herbs, coarse roots and fine roots, was determined with the micro-analysis[26] method:

$$NPP = \Delta B = \frac{B_2 - B_1}{t_2 - t_1} + H + D, \tag{1}$$

where B_1 is biomass ($\text{g} \cdot \text{m}^{-2}$) in time t_1 and B_2 in time t_2; H is predation by animals during t_2-t_1; the unit is $\text{g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$; D is the amount of litter fall during t_2-t_1 and the unit is $\text{g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$.

Animal-consumed biomass was ignored because the proportion is considered tiny and the amount is difficult to estimate.

DBH regression models, both in-bark and over-bark, were established to estimate DBH in the past years. Thus, the biomass of the canopy layer in the past was acquired. NPP of canopy layer was estimated with these components in addition to litter fall data.

(3) Biomass and productivity of understory. Biomass of shrubs and herbs was investigated by harvesting in 18 quadrates, each with a size of 1m × 1 m.

To estimate the understory NPP, the ages of herbs and shrubs were arbitrarily assigned as 3 and 6 years, respectively. Fine-root ($0.28\text{ mm} < D < 2\text{ mm}$) biomass was surveyed in 8 quadrate columns, each with a base area of 0.625 m^2 and 0.40 m in depth. Roots were weighed after washing off soil. According to a previous report[27], the turnover cycle of fine roots in subtropical coniferous forests is about 3 to 5 years, so the mean value of 4 years was adopted in this study.

(4) Litter fall observation. From 1992 to 2005 excluding 1997 and 1998, both fresh and dry weight of litter fall were measured monthly in 2 plots with 6 traps, each with a size of 1 m^2. Data for 2 months in 1986 were lost due to mismanagement. All data gaps were filled with the observation data of adjacent years.

(5) Biome-BGC modeling. Biome-BGC[22] is an ecological model that estimates fluxes and storage of energy, water, carbon and nitrogen for vegetation and soil components of terrestrial ecosystems. It requires meteorological data and soil and vegetation constants as input to simulate key ecosystem processes including photosynthesis, respiration and decomposition to yield ecosystem fluxes of energy and mass.

Flux estimated with the Biome-BGC model (http://www. ntsg.umt.edu) strongly depends on daily weather conditions. Site parameters include the description of geography and physics. Some physiological parameters were based on *in-situ* observation and the others were assigned as default. As to the meteorological data, it requires six categories of information: daily maximum temperature ($T_{\max}$, ℃), daily minimum temperature ($T_{\min}$, ℃), average daytime temperature (T_{day},℃), daily precipitation (*prcp*, cm), daytime average vapor pressure deficit (VPD, Pa) and daytime average short wave radiant flux density (*srad*, $\text{W} \cdot \text{m}^{-2}$). Because solar radiation was not observed until 1998 in the site, it has to be interpolated for the period of 1985—1998. The Mountain Microclimate Model (MT-CLIM) (http://www.ntsg.umt.edu/) was adopted to estimated radiation. And an empirical model was introduced for deducing solar radiation based on the observed data from 1998 to 2004.

Precipitation and water vapor pressure create significant influences on radiation[28]. By adding maximum temperature and evaporation to the regression model, two localized models for Qianyanzhou were established. As a test, for the year 2005, the estimated values were quite similar to observed values. The models (eqs. (2) and (3)) are shown as follows:

For rainy day,

$$Q_1 = -64.348 + 1.598E + 38.969L + 0.174Q_0 - 0.868P - 6.649(S_A / S_0),$$

$$(R{=}0.802,\ R^2{=}0.644,\ F{=}381.79,\ Sig < 0.001); \quad (2)$$

For no-rain day,

$$Q_2 = 112.451 - 2.752E + 43.497L + 0.05385Q_0 + 144.35(S_A / S_0),$$

$$(R{=}0.911,\ R^2{=}0.831,\ F{=}643.88,\ Sig < 0.001); \quad (3)$$

where Q_1 is the average solar radiation on rain day ($\mathrm{W \cdot m^{-2}}$), Q_2 the average solar radiation on no-rain day ($\mathrm{W \cdot m^{-2}}$), Q_0 the average daily astronomical radiation ($\mathrm{W \cdot m^{-2}}$), E the average daily water vapor pressure (hPa), L the daily evaporation (mm), S_A/S_0 the sunshine percentage(%), S_A the sunshine hours (h), S_0 the astronomical reasonable sunshine hour (h) and P the precipitation(mm).

2 Results

2.1 Biomass and NPP distribution pattern of slash pine community

The biomass of *Pinus elliottii* plantation was 10574 $\mathrm{g \cdot m^{-2}}$ (Figure 1), with a ratio of 3.57 between aboveground and underground biomass. Accumulated litter fall was estimated to be 1631 $\mathrm{g \cdot m^{-2}}$, with a ratio of 6.48 between biomass and litter accumulation. Biomass of the high canopy layer, shrub layer, herbaceous layer, tree roots, herbaceous and shrub roots and fine-roots (0.28 mm < roots < 5 mm) were 7542, 480, 239, 1810, 230, 274 and 239 $\mathrm{g \cdot m^{-2}}$ (as shown in Figure 1), respectively. Canopy layer biomass accounted for 71.33% of community biomass and 21.88% of root biomass. Fine root biomass accounted for 2.59% of community and 11.82% of below-ground biomass.

In the canopy layer, the ratio between aboveground biomass and root biomass was 4.3, which was smaller than the ratio 7.64 measured in a slash pine forest in Guangxi, southwest China[29]. The ratio between the coarse root (>5 mm) biomass and fine-root biomass was 6.6 for the high tree layer and 8.3 for the community.

The NPP of the slash pine plantation was 1027.1 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$. The recent 5-year mean NPP of the high tree layer (including tree roots), shrub layer (mean age 6), herbaceous layer (age 3), herbaceous and shrub roots (age 3) and fine roots (0.28 mm < roots < 2 mm) measured 741, 62.18, 79.55, 76.60 and 68.38 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$, respectively. Tree-layer NPP accounted for 72.1% of community NPP. Herbaceous and shrub layers and fine roots contributed as much as 27.9% of the community NPP. In the canopy layer, the proportion of biomass was approximately identical with that of NPP.

2.2 Empirical DBH regression models and NPP of canopy layer

Based on stem analysis, 17 empirical DBH regression models were constructed as shown in Table 2.

DBH regression models showed high correlation coefficient (R^2) among the consecutive years but it also

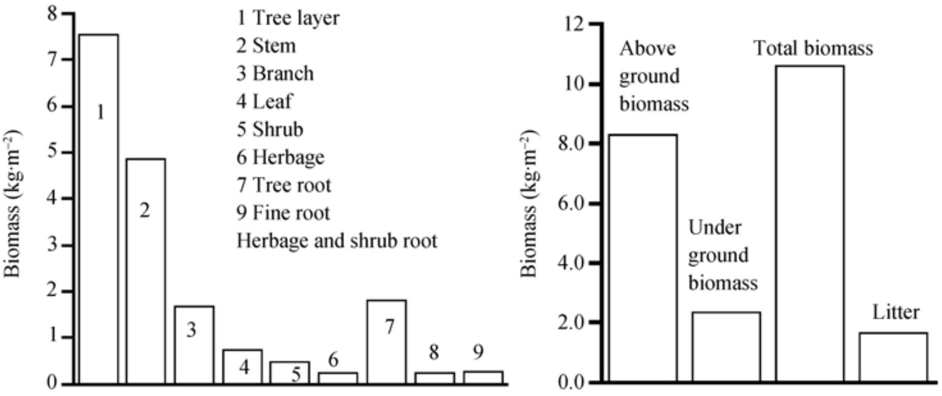

Figure 1 Biomass structure of *P. elliottii* forest.

Table 2 Predictive equations for DBH of *P. elliottii* in different years

Regression models	R^2	F	Mean	Std.
$DBH_{\_1987}=0.06814D_{\_2004}$-0.862	0.174	11.8	0.32	0.63
$DBH_{\_1988}=0.167D_{\_2004}$-1.724	0.314	25.6	1.18	1.14
$DBH_{\_1989}=0.288D_{\_2004}$-2.778	0.482	52.2	2.23	1.59
$DBH_{\_1990}=0.384D_{\_2004}$-3.032	0.568	73.7	3.64	1.95
$DBH_{\_1991}=0.447D_{\_2004}$-2.88	0.621	91.8	4.89	2.17
$DBH_{\_1992}=0.5D_{\_2004}$-2.597	0.653	105.3	6.09	2.37
$DBH_{\_1993}=0.55D_{\_2004}$-2.27	0.689	124.2	7.28	2.54
$DBH_{\_1994}=0.615D_{\_2004}$-2.075	0.744	162.6	8.62	2.73
$DBH_{\_1995}=0.664D_{\_2004}$-1.781	0.790	210.7	9.75	2.86
$DBH_{\_1996}=0.711D_{\_2004}$-1.498	0.833	280.1	10.85	2.98
$DBH_{\_1997}=0.766D_{\_2004}$-1.386	0.869	371.9	11.92	3.15
$DBH_{\_1998}=0.773D_{\_2004}$-0.872	0.896	484.8	12.55	3.13
$DBH_{\_1999}=0.803D_{\_2004}$-0.617	0.933	780.2	13.34	3.19
$DBH_{\_2000}=0.834D_{\_2004}$-0.428	0.955	1188.2	14.06	3.27
$DBH_{\_2001}=0.887D_{\_2004}$-0.546	0.980	2701.5	14.87	3.43
$DBH_{\_2002}=0.942D_{\_2004}$-0.645	0.992	6851.3	15.72	3.62
$DBH_{\_2003}=0.973D_{\_2004}$-0.603	0.996	15193.1	16.29	3.73

showed a declining trend when the interval exceeded five years. The shorter the time interval, the more precise the model forecast.

For the canopy layer, annual litter fall was higher than biomass increment. But they were highly correlated ($Y = 1.19X$, where Y is litter fall and X is biomass increment) with a correlation coefficient (R^2) of 0.885 using 12 years' litter fall data. The biomass increment was highly correlated to litter fall in the following year, with an equation of $Y = 1.26X$ ($R^2 = 0.683$), where Y is biomass increment and X is litter fall in the following year.

Figure 2 indicates that both biomass increment and the litter fall showed an increasing trend with some fluctuations in the past 18 years. The carbon sequestration ability of the young plantation increased progressively, implying that reforestation is an efficient strategy for carbon sink. From 1999 to 2004, the average annual biomass increment and litter fall were 741 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$ (381.31 $\mathrm{gC \cdot m^{-2} \cdot a^{-1}}$) and 849 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$ (463 $\mathrm{gC \cdot m^{-2} \cdot a^{-1}}$), respectively, with a peak (933 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$) in 2002. The biomass increment was quite similar in 1999 (666 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$) and in 2000 (677 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$) but sharply decreased in the drought years of 1998 and 2003. The highest litter fall was 999 $\mathrm{g \cdot m^{-2} \cdot a^{-1}}$ in 2002.

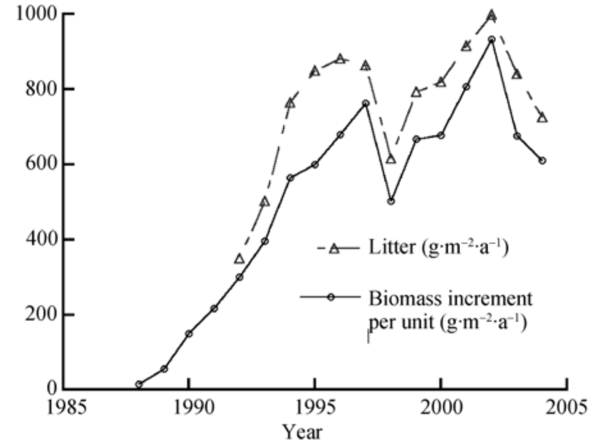

Figure 2 Inter-annual change of biomass and litter fall of *P. elliottii* forest.

2.3 Simulation by BGC model

Figure 3 shows the annual changes of NPP, gross primary production (GPP), maintenance respiration (MR) and max leaf area index (LAI) simulated by BGC over the period from 1985 to 2005.

In order to better understand the relationship between quality of data and model parameters, four combinations of input data and parameter set were designed as follows:

(1) BM, all default parameters of BGC model and radiation data derived by MT-CLIM.

(2) BQ, all default parameters of BGC model and radiation data derived by empirical regression model for Qianyanzhou.

(3) QQ, part of eco-physiological constants measured by Qianyanzhou ecological Station and the radiation data derived by empirical regression model.

(4) QM, part of eco-physiological constants measured by Qianyanzhou ecological Station and the radiation data derived by MT-CLIM.

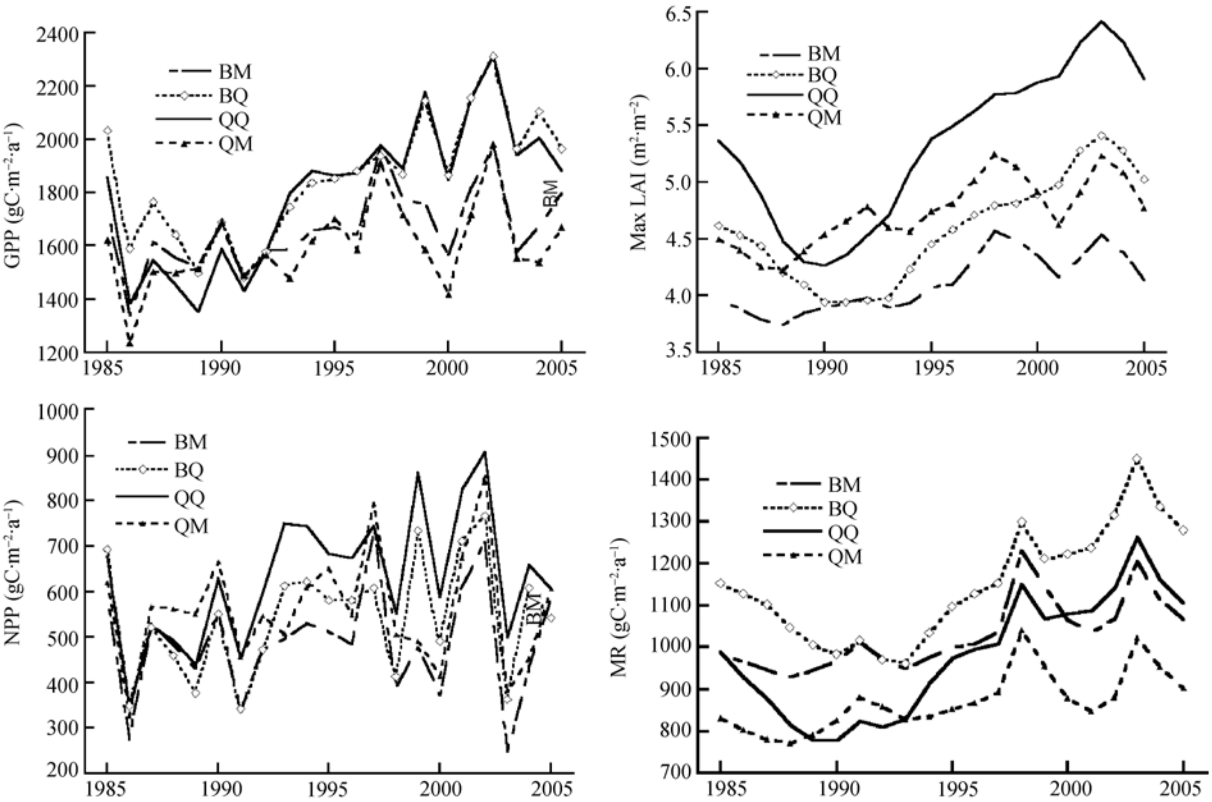

Figure 3 Ecosystem productivity simulated by BGC model.

Among these simulations, the results of the QQ design were the closest to the measured values. By combining BGC with QQ, the average NPP was estimated to be 630.88 g C·m^{-2}·a^{-1} with minimum value in 1986 (343.31 g C·m^{-2}·a^{-1}) and maximum value in 2002 (906.42 g C·m^{-2}·a^{-1}). From 1985 to 2005, average annual GPP, MAX LAI, MR, evapotranspiration and outflow were estimated to be 1 800 g C·m^{-2}·a^{-1} (1351.62 — 2318.26 g C·m^{-2}·a^{-1}), 5.32(4.2 — 6.41), 980.05 (776.52—1262.40 g C·m^{-2}·a^{-1}), 110.56 cm·a^{-1} (84.18 —133.18 cm·a^{-1}) and 37 cm·a^{-1} (0—98.82 cm·a^{-1}), respectively.

NPP, GPP and MAX LAI estimated by BGC in combination with QQ were the largest among all designs. As an example of NPP simulation, by comparing BM, MQ and QM with QQ, the average differences were –21.77% (–50.35% — 0.01%), –13.75% (–26.97% — 2.12%) and –9.3% (–43.11%—25.53%), respectively.

Simulated GPP can be classified into 2 types according to ecophysiological constants. And simulated NPP, MR, and MAX LAI showed large variability under different parameter combinations.

2.4 Model validation

The carbon content of trunk, branch and leaf was 51.17%, 51.37% and 53.35%, respectively, provided by the experimental station. The carbon densities in roots of shrubs and herbages were 54.53% and 68%[30]. It was calculated at 51.46% for the total aboveground vegetation.

There was a linear relationship between simulated and measured NPP (Figure 4) ($Y = 0.931X$, where Y is measured and X is simulated NPP) and the correlation coefficient (R^2) was 0.48. By contrast, for the last 10 years, the relationship between the two could be expressed with a parabolic equation in the form of $Y = 0.00144 - 2.47X + 0.00215X^2$ ($R^2 = 0.53$). The estimated NPP was principally consistent with the measured values, although the simulated curve showed less fluctuation compared with the actual process. The simulated NPP was 12.38% lower than measured NPP; but ranged between –38.38% and 11.21%.

Since the Biome BGC model is based on meteorological factors without considering stand age, the simulated NPP before 1995 was significantly higher than the real value (Figure 5). Apparently, within 8 years after

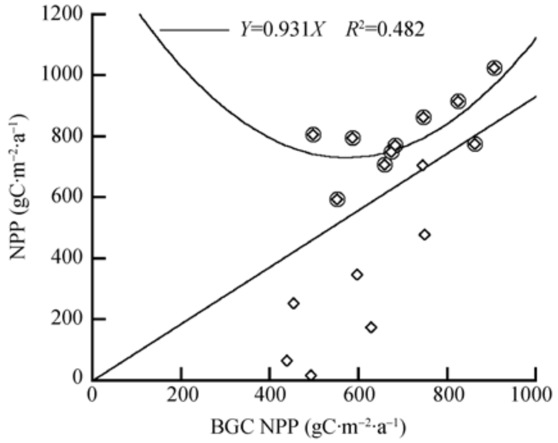

Figure 4 The comparison between BGC simulation and measured NPP.

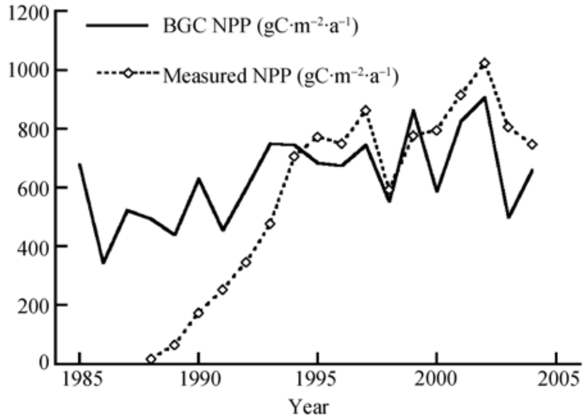

Figure 5 BGC-simulated and measured NPP from 1985 to 2004.

afforestation, the canopy layer was very sparse in coverage and the simulated results, therefore, greatly differed from the measured values. The tested NPP consists of both underground and aboveground parts of the canopy layer only. NPP of shrubs and herbs (both aboveground and underground) and fine roots, was 286 $g \cdot m^{-2} \cdot a^{-1}$ in total, or 38.69% of the tree-layer NPP.

The measured NPP of the forest stand was significantly higher than the value simulated by the BGC model. From a global perspective, as a result of the control of subtropical high pressure, this region has a relatively dry climate, which causes low primary productivity. In the test site, however, typical subtropical monsoon climate is predominant and the air mass is moister than most areas along this latitude. Because monsoon climate is not considered in the algorithm, the simulation presented some inconsistency with measured values.

The NEE observed by eddy covariance was 12.97% (on average) higher than measured NEP from 2003 to 2005 (Table 3). NEE in 2004 was very close to measured NEP, with a difference of only 73 g C $m^{-2} \cdot a^{-1}$, which is close to international mainstream error sources, ± 50 g C $m^{-2} \cdot a^{-1}$[31]. Measured NPP was 22.55% higher than the simulated value.

Although it was extremely dry, NPP was the highest in 2003. A possible reason for this is that the NPP of herbages, shrubs and fine roots as constants was large in addition to a dramatic increase in litter fall. Besides, the BGC model does not consider the time lag of ecosystem processes.

Table 3 Carbon budget of the plantations in Qianyanzhou (g C $\cdot m^{-2} \cdot a^{-1}$)

Year		2003	2004	2005	Mean
EC^a)	NEE	387.2	423.8	691.6	500.9
	RE	1223.3	142	1226.7	1297.3
	GEE	1610.4	1865.9	1918.2	1798.2
BGC modeling	NPP	497.1	659.2	605.3	587.2
	GPP	1941.2	2003.5	1881.6	1942.1
	MR	1262.4	1161.3	1105	1176.3
Forest survey	Canopy layer NPP	806.9	747.6	720.2 e)	758.2
	Litter per year	459.1	395.3	380.9	411.8
	Annual Biomass Increment of canopy layer	347.7	352.3	339.3	346.4
	Forest communities NPP^c)	1092.9	1033.6	1006.2	1044.2
Soil respiration^b)	NEP^d)		497.1	374.7	435.9
	With litter covered		536.5	631.5	584
	No litter covered		327.5	394	360.8

a) EC (by eddy covariance)1); b) Soil respiration by static observation[32]; c) Community NPP equal to tree-layer NPP plus the rest items (286 g C $\cdot m^{-2} \cdot a^{-1}$); d) NEP=community NPP-soil respiration; e) Net increment in 2005 estimated based on litter fall.

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1) Liu Y F. Flux observation and carbon budget in Qianyanzhou (no published). 2008

Soil respiration was active with a yearly average of 584 g C·m^{-2}·a^{-1}. Ecosystem respiration (Re) observed by the flux tower was similar to maintenance respiration (MR) simulated by the BGC model, with an average difference of 9.3% (3.1%—19.4%).

Based on the simulation, the pattern of productivity is summarized as follows. NPP and MR accounted for 30.2% (25.6%—32.9%) and 60.5% of GPP, respectively. NEP accounted for 57.5% (48.1%—66.5%) of tree-layer NPP and 41.74% (37%—52%) of total stand NPP. Soil respiration was 77.0% of measured tree NPP and 55.9% of measured community NPP. Soil respiration was approximately the same as litter fall, with the ratio between the two being 1.05 (0.99—1.26).

3 Discussion

Based on investigation and long-term observation, carbon stock and the NPP pattern of slash pine plantation were analyzed and the growing process of NPP over 21 years was simulated with Biome BGC.

Preliminary study results are as follows:

(1) From 1999 to 2004, the average annual growth rate and the litter fall were 741 g·m^{-2}·a^{-1} (381.31 g C·m^{-2}·a^{-1}) and 849 g·m^{-2}·a^{-1} (463 g C·m^{-2}·a^{-1}), respectively. There was significant correlation between annual litter fall and annual biomass increment and litter was 1.19 times greater than the biomass increment of living trees. From 1985 to 2005, NPP and GPP by BGC modeling were 630.88 (343.31—906.42 g C·m^{-2}·a^{-1}) and 1800 g C·m^{-2}·a^{-1} (1351.62—2318.26 g C·m^{-2}·a^{-1}), respectively.

(2) A linear relationship (R^2=0.48) exists between measured and simulated NPP of the canopy layer.

(3) NPP accounted for 30.2% (25.6%—32.9%) of GPP. NEP accounted for 57.5% (48.1%—66.5%) of canopy layer NPP and 41.74% (37%—52%) of stand NPP. Soil respiration accounted for 77.0% of measured tree NPP; and 55.9% of measured stand NPP.

(4) NEE by eddy covariance was 12.97% higher than observed NEP. The measured NPP of forest communities was significantly higher than the one simulated by the BGC model.

(5) Since time lag is little considered in the BGC model, especially at a regional scale, the simulated values may be lower than actual values.

Ecosystem carbon fluxes can be measured continuously using eddy covariance techniques and the relationship between carbon fluxes and environmental variables can be acquired. This is significant for clarifying the ecosystem process and its coupling mechanism with environmental variables. By contrast, traditional methods of stand survey only focus on plants and the contribution to carbon storage can be specifically identified.

Definitely, there is inconsistency between the two approaches. NEE by eddy covariance was slightly higher than NEP as measured by biomass survey. On one hand, in the process of calculating forest NEP from measured NPP, soil respiration included the root respiration and soil microbial respiration. We need to further distinguish these two parts of respiration. On the other hand, it was impossible to accurately measure fine-root turnover rate, so the survey values for fine root NPP may be underestimated. Thus, the value of NEP has been underestimated to some extent.

BGC model simulation was apparently affected by the input ecophysiological constants. Overall, it was difficult to obtain all the measured parameters. BGC model needs as many as 34 types of parameters, some of which are very difficult to collect and have not even been studied in China. The data quality was another factor， which may have affected simulation results. Although meteorological data have been observed at Qianyanzhou Biological Station continuously over 20 years, radiation, for example, had not been observed until the past 8 years. Many data points had to be interpolated. NPP simulated by BEPS based on meteorological data released by the National Center for Atmospheric Research (NCAR) was 15% lower than that simulated by the same model with data from Japan Meteorological Association (JWA)[3]. The results of this study showed that relative errors of estimated NPP in different combinations were even greater than those from different sources of data.

The mean aboveground biomass was 256 g·m^{-2}(227—294 g·m^{-2}) [23] in 1983, when the station was established before afforestation, and it turned out to be 8 261 g·m^{-2} in 2005, increasing 32.3 times. The mean annual biomass increment was 348 g·m^{-2}. So the forest was evidently functioning as a carbon sink. The biomass of coarse roots (>5 mm) was over 8.3 times the fine root biomass and this ratio was slightly smaller compared to that of a European beech (*Fagus sylvatica*) forest (10 times)[33]. In this study, the NPP of fine roots accounted for 6.67% of the total community NPP, which was lower than that of a 40-a *Picea abies* forest in Norway (13%)[34]. With forest growth, the proportion of fine roots is expected to increase. The turnover rate of fine roots is significantly faster than that of coarse roots, which is currently a popular topic in ecosystem studies yet difficult to quantify[35,36].

The growing diameter at breast height (DBH) can be directly measured in the field. Therefore, it is a suitable way to study NPP of mixed forest by monitoring tree diameter and collecting litter fall. And the results can be compared with NEE values observed by eddy covariance methods[37]. It is possible to reduce the system error by stem analysis. However, self-thinning of forest must be considered when evaluating carbon balance. Based on data acquired in 1990[38], 1994[39], 1997[40], 1999[41] and the present survey, the process of forest thinning was simulated as shown in Figure 6. Due to dieback, litter fall decreased to 0.11 $g\cdot m^{-2}$ (about 0.03% of annual forest biomass increment), which was not included in the calculation of NPP. Thus, accurate estimation of NPP should be based on long-term monitoring with a uniform standard.

Simulations with 17 ecosystem process models demonstrated that global and regional NPP is sensitive to available water[19]. It is estimated that the proportion of vegetation on the globe with growth limited by water availability is 40%, and that limited by temperature and radiation is 33% and 27%, respectively[42].

After reviewing 49 studies on forest NPP over 55 years, we found that less than 7% of forests were in severely water-limited systems[43]. This paper shows that the NPP model simulation was sensitive to water conditions as shown in Figure 7. There were two drought years (1986 and 2003), and the simulated values were accordingly smaller. The difference in NPP from 2003 to 2004 was 162 $g\ C\cdot m^{-2}\cdot a^{-1}$, according to simulation. In addition, the differences between simulation and tested results for the 2 years were not significant, being 59 and 36 $g\ C\cdot m^{-2}\cdot a^{-1}$, respectively.

We can conclude that the ecosystem had a buffering effect under extreme weather conditions. Therefore, the time-lag effect should also be taken into account when NPP is simulated by process model. "The combined and interaction effects of temperature, radiation and precipitation change with the positive effect of CO_2 concentration, the negative effects of O_3 and other pollutants. And the present positive effects on NPP would not be elucidated with experimental manipulation of one or a few factors at a time"[43]. Long-term field monitoring and flux measurement are essential for obtaining robust information on carbon cycling. Furthermore, the study of future carbon cycling will mostly rely on remote sensing data on regional scales[20]. The development of relevant models is of great help to measuring carbon budgets by combining remote sensing images and ecological algorithms[44].

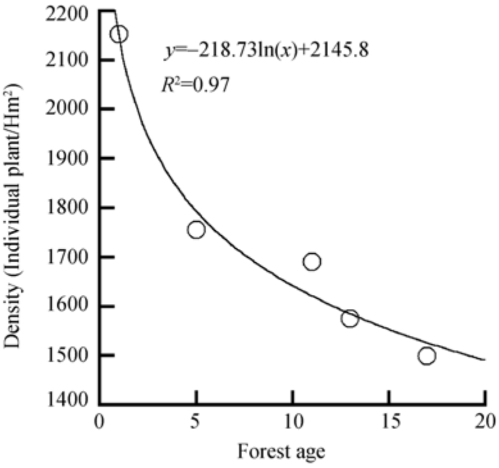

Figure 6 The relationship between forest age and forest density.

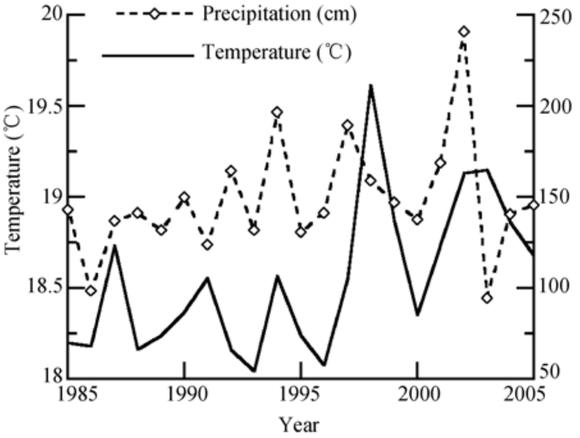

Figure 7 The annual mean temperature (℃) and annual mean precipitation(cm) from 1985 to 2005 in QYZ.

At present, there is no model that fully considers the role of subtropical monsoon climate in this region. The NPP was higher in this region than in other areas at similar latitudes. Trees showed vigorous growth in February, April, May and August. The regression coefficient between volume increment and maximum temperature in May was 0.6, while the coefficients in August between volume increment and precipitation, evaporation and air temperature were 0.44, 0.44 and –0.39, respectively.

Changes in carbon sequestration[45] and the soil carbon pool[46] in Qianyanzhou ecological Station were recently reported, so that we did not specifically discuss soil carbon here.

In brief, ecosystem carbon cycling research should include robust data from long-term observation as a fundamental approach. Various methods describing ecosystem processes and function, such as multi-scale simulation and observation, are helpful to ecosystem management and understanding of global environment issues.

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