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REGULAR ARTICLE

Potential for forest vegetation carbon storage in Fujian Province, China, determined from forest inventories

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Abstract Carbon storage in forest vegetation of Fujian Province plays a significant role in the terrestrial carbon budget in China. The purposes of this study are: (1) to evaluate how the afforestation and reforestation programs established in Fujian Province influence carbon storage in forest ecosystems; (2) to assess the influence of tree species, forest age and ownership changes on vegetation carbon storage; and (3) to explore strategies for increasing vegetation carbon potentials. Data from seven Chinese Forest Resource Inventories and 5,059 separate sample plots collected between 1978 and 2008 were used to estimate vegetation carbon storage in the whole province. In addition, uncertainty analysis was conducted to provide the range of our estimations. Total forest vegetation carbon storage increased from 136.51 in 1978 to 229.31 Tg C in 2008, and the forest area increased from 855.27×10^4 to $1,148.66\times10^4$ ha, showing that the Fujian forests have a net vegetation carbon increase of 96.72 Tg C with an annual increase of 4.84 Tg C over the study period. Carbon storage varied with dominant forest species, forest age and forest ownership, suggesting that increases in vegetation carbon potentials can be achieved through selection of forest species and management of age structures. Implementation of afforestation and reforestation programs in Fujian Province over the past three decades

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has made a significant contribution to forest carbon storage. Vegetation carbon storage can be further increased by increasing the proportion of mature, broadleaved and state-owned forests.

Keywords Forest carbon storage · Forest resource inventory · Reforestation · Carbon potential · Fujian Province

Introduction

Forests are an important component of terrestrial ecosystems, with forest area and carbon storage accounting for 66% and 80% of land area and terrestrial carbon storage, respectively (Pregitzer and Euskirchen 2004). Dynamic changes in vegetation carbon storage play a critical role in maintaining the global carbon balance (Houghton et al. 2000). From a carbon budget perspective, forest changes as a result of deforestation or reforestation can result in forests being either carbon sources or carbon sinks (Noble and Dirzo 1997). Hence, forest management can determine the direction and strength of vegetation carbon storage capacity (Karjalainen 1996; Niu and Duiker 2006). Because of this, increasing vegetation carbon sequestration through forest protection and reforestation has been widely recognized as an important strategy to combat the impacts of climate change (Pfaff et al. 2000; Fang et al. 2001).

Currently, about US$ 0.15b has been invested in afforestation world-wide in order to increase vegetation carbon sequestration. At the Copenhagen Climate Change Conference in 2009, the participating countries agreed that another US$ 3.5b should be invested in reducing felling and carbon emissions caused by forest degradation. It is expected that vegetation carbon sequestration will inevitably become part of carbon trading (Bodansky 2010). Evaluation of the carbon cycle of forest ecosystems is not only vital to accurately estimating the global carbon budget and the influence of potential climate change on terrestrial ecosystems, but it is also the key to fulfilling international conventions, such as the United Nations Framework Convention on Climate Change and the Kyoto Protocol and as a basis for appropriate policies (Masera et al. 2003; Lee et al. 2005; Torres et al. 2009). This is relevant because different tree species and tree ages have different carbon sequestration rates, and so do reforestation practices (Song and Woodcock 2003; Zhao et al. 2010). If the influence of these factors on carbon storage is not taken into consideration, it is difficult to provide a scientific basis for designing management strategies and policies to increase forest carbon. Furthermore, it is not possible to provide robust data to support international trade negotiations on carbon and climate change (Liu et al. 2006). Therefore, evaluation of vegetation carbon storage in association with forest species, forest age structures and management is needed to enable accurate quantification of forest vegetation carbon dynamics and potentials (Ward and Johnson 2007).

Long-term monitoring of vegetation carbon storage at regional and national levels is beneficial for assessing vegetation carbon storage and the possible drivers influencing vegetation carbon changes (Moncrieff and Leuning 1996). Given that China is a large country with many types of forest ecosystems (from tropic rainforests in the south to boreal forests in the north), it is challenging to rely on the limited monitoring data to quantify regional or national vegetation carbon storage and dynamics. Fortunately, China has implemented a nationwide Forest Resources Inventory Program since the 1970s. The program involves an intensive survey of permanent sampling plots once every 5 years. Up to now, China has conducted seven inventories. Data from this large database together with successful implementation of significant reforestation programs in the past several decades in China provide an excellent and unique opportunity to assess forest recovery and their effects on carbon storage in China (Shin et al. 2007).

Fujian Province is one of the four major forest regions in China. It has the highest forest coverage rate (63.1%) in the country, with a forest area of 9.15 million hectares and a total timber volume of 532.26 million cubic meters. In order to combat many environmental problems, Fujian province, like other provinces in China, has successfully implemented a series of reforestation programs such as the "National Forestation Program," "Natural Forest Conservation Program" and "Sloping Cropland Conversion Program" (Ren et al. 2011). These programs have noticeably increased the forest area and vegetation carbon storage in the province (Fig. 1). However, most of the past afforestation and reforestation programs in Fujian Province focused on increasing the forest area with little attention on the quality of forest recovery. Consequently, although the forest

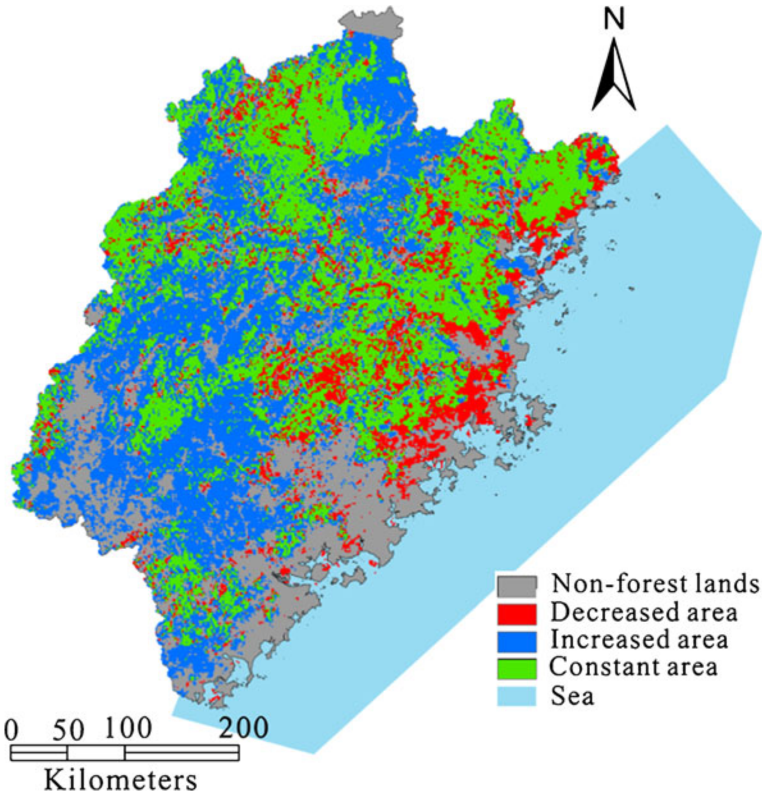


Fig. 1 Change in forest area from 1988 to 2008 in Fujian Province

coverage is high, most are young and middle-aged single-species forests, and the carbon density is far below the global average level of 80.60 Mg C/ha reported by Jiao and Hu (2005) (Table 1). Besides, rapid economic development in the province has led to significant human disturbance (e.g., land use and land cover change) and growing conflict between economic development and environmental protection. Vegetation carbon density (Mg C/ha) is the most important component of carbon sequestration and indicates the carbon sequestration ability of the vegetation, as well as reflecting the degree of disturbance (Desai et al. 2008; Potter et al. 2008).

The objectives of this paper are: (1) to use the Forest Resources Inventory data to assess how the afforestation and reforestation programs established in Fujian Province influence vegetation carbon storage; (2) to assess the influence of tree species, forest age and ownership changes on vegetation carbon storage; and (3) to identify possible forest management strategies for increasing vegetation carbon potentials in Fujian Province.

Table 1 Forest area, total carbon storage, and carbon density in seven inventory periods from 1978 to 2008 in China

Area	Inventory time	Forest area (10^4ha)	Total carbon (Pg C)	Carbon density ($Mgha^{-1}$)	Carbon change ($PgCa^{-1}$)
China	1974–1978	10,822	3.8488	35.56	n.a
	1979–1983	9,562	3.6960	38.65	−0.0306
	1984–1988	10,219	3.7590	36.78	0.0126
	1989–1993	10,864	4.1138	37.87	0.0710
	1994–1998	12,920	4.6563	36.04	0.1085
	1999–2003	14,279	5.5064	38.56	0.1700
	2004–2008	15,515	6.0822	39.20	0.1152

Data are from Jiao and Hu (2005)

Materials and methods

Site description

Fujian Province is situated in southeastern China from 115°50′to 120°43′E and 23°32′to 28°19′N, and has an area of 121,400 km^2. It has a middle sub-tropical and south sub-tropical humid monsoon climate with an annual average rainfall of 1,670 mm and annual average temperature of 17–20°C. Over 85% of the province is mountains and hills with many faulted landforms and basin valleys, and an irregular coastline with numerous bays and islands (Fig. 2). Based on the Soil Taxonomy of China, the soils are mainly latosolic red soils, red soils, yellow soils and mountain meadow soils. The main indigenous and secondary vegetation types include south sub-tropical rain forest, middle sub-tropical evergreen broad-leaved forest, bamboo forest, mixed conifer and broadleaved forest and a sub-tropical understory (Lv et al. 2010).

Data source

China's National Forest Inventory (NFI) provides a source of forest inventory data. They can be used for estimating changes in vegetation carbon storage for any region. At present, there are over 5,000 permanent sample plots (square plots is 0.067 ha in area with a minimum inter-plot spacing of 4×6 km) spread across Fujian Province, which have been used for seven systematic forest resource surveys from 1978 to 2008.

Survey data included land uses, tree growth and various other ecological and site variables. Compasses were used to measure orientation and tapes to measure distances. Surveys were conducted every 5 years with individual standing trees identified by oil paint number, plates and signs at the point of DBH. Tree height and DBH (we measured the inside bark) for each tree were measured, and tree volumes were calculated using a single entry volume table.

Forest temporal and spatial distributions

To measure forest distribution and change from 1988 to 2008, NOAA-AVHRR images were used. The original Level 1B AVHRR datasets were provided by the National Oceanic and Atmospheric Administration (NOAA) through the Comprehensive Large Array-data Stewardship System (CLASS). Twenty images acquired in summertime for each year were selected according to atmospheric and meteorological conditions. The normalized differential vegetation index (NDVI), which has been widely used for vegetation, was calculated based on images after being geo-referenced and radiometrically corrected. The influence of clouds and heavy aerosols was taken into account by considering the maximum NDVI value in each year's summertime image at each pixel to be the factual value for that year. Suitable thresholds were determined separately to obtain forest distribution in each year from the NDVI results.

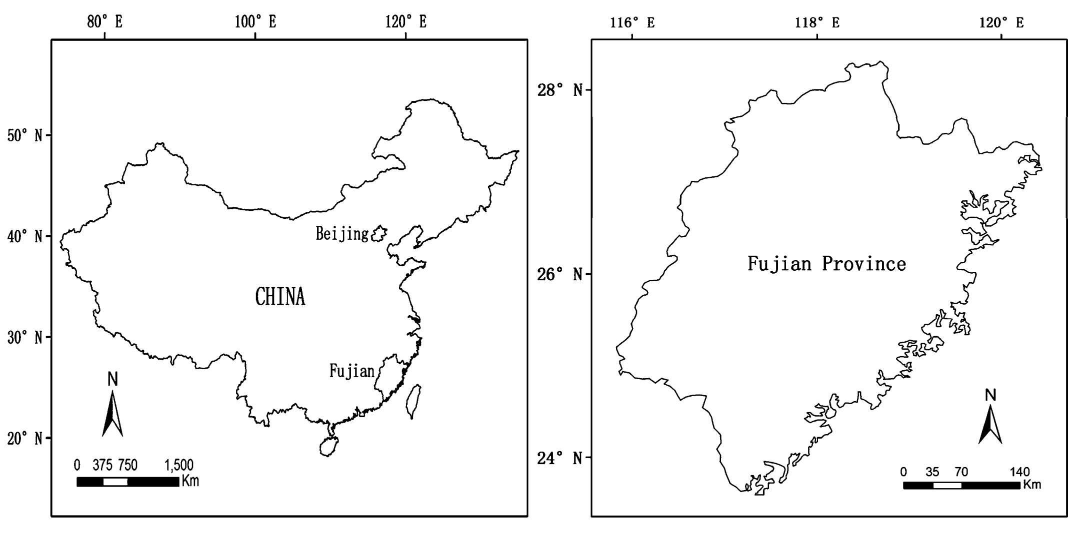


Fig. 2 The location of Fujian Province, South China

Forest biomass estimation

Forest biomass was estimated using the continuous function suggested by Fang et al. (2001), the regression function of which is represented by B = a × V + b, where B is the biomass per hectare (Mg/ha), V is the volume per hectare (m^3/ha), and a and b are parameters. We selected 11 dominant tree species among the 272 samples for volume and biomass regression equations.

The inventory data record 21 forest species groups, of which the parameters for 8 groups were used in this study because the forest inventory data only selects records of dominant tree species. The parameters for another three forest species groups including mixed conifer forest, mixed conifer and broadleaved forest and mixed broadleaved forest were taken from Zhang and Wang (2008). Table 2 lists the parameters of forest volume-biomass that were used in this study.

In the Forest Resources Inventory data, Fujian Province forests include six forest categories including (1) closed forests (forests stands with coverage of greater than 0.2), (2) open forest (forest stands with coverage of less than 0.2), (3) economic forests (forests for economic purposes other than timber value), (4) bamboo forests, (5) shrub forests and (6) trees on non-forested land. However, the surveys do not contain any calculation of the volumes of economic forests, bamboo forests and shrub forests. Consequently, there are no corresponding volume-biomass conversion models for these forest categories. This study applied a document method to estimate the values of economic forests, bamboo forests and shrub forests, while the biomass of trees on non-forest land was obtained through conversion of stumpage volumes. The specific calculation method and parameters used were as follows: for bamboo forests, the single average biomass of 22.5 kg multiplied by the total number of trees; for economic forests, the average biomass per unit area (11.85 Mg/ha) multiplied by the total area of this forest type; for shrub forests and sparsely forested areas, the average biomass per unit area (19.76 Mg/ha) multiplied by the total area of these forest stand types; and for scattered trees, the average conversion parameters obtained by dividing forest stand biomass by stand volume, using data from Fujian Province for the same period.

The Fujian provincial forests can also be divided into coniferous and broadleaved forests. The coniferous forests can be further classified into conifers, including eight dominant tree species, *Pinus thunbergii*, *Pinus massoniana*, *Pinus elliottii*, *Pinus taeda*, *Keteleeria fortunei*, *Cunninghamia lanceolata, Keteleeria*, and mixed coniferous forests. The broadleaved forests can be divided into two main types: hard broadleaved forests and soft broadleaved forests, including eight dominant tree species (*Quercus acutissima*, *Lauracea*, *Schima superba*, *Eucalyptus*, *Acacia*, *Casuarina*, mixed broadleaved forests, and mixed conifer and broadleaved forests).

Determining the maturity of forests

Data on the average age for dominant tree species in each of the sample forest stands and sample open forest plots have been recorded. Five age groups are used to classify the maturity of forests. These include young forest, middle-aged forest, premature forest,

Table 2 Parameters used to calculate biomass expansion factors (*BEF*) (BEF is expressed as a function of stand timber volume (*v*), $BEF = a \times V + b$, where *a* and *b* are constants for a particular forest type; Data are based on direct field measurements)

Forest type	*a*	*b*
Casuarina equisitifolia	0.7441	3.2377
Cunninghamia lanceolata	0.3999	22.5410
Eucalyptus	0.8873	4.5539
Mixed broad-leaved forests	0.8392	9.4157
Mixed conifer and broad-leaved forests	0.7143	16.9154
Mixed conifer forests	0.5894	24.5151
Nonmerchantable woods	0.7564	8.3103
Quercus acutissima	1.1453	8.5473
Pinus. massoniana, Pinus. elliottii, Pinus. taeda	0.5101	1.0451
Pinus. thunbergii, Other *Pinus*	0.5168	33.2378
Populus group	0.4754	30.6034

mature forest and post-mature forest. The full definition of each age group is shown in Table 3.

Determining the ownership of forests

The Fujian forests can be classified into state-owned (forests and lands owned by the nation) and community-owned (forests and lands managed by communities) forests according to forest ownership.

Estimation of forest vegetation carbon storage

Estimation of forest vegetation carbon storage using established relationships between forest biomass and volume has been widely applied (Fang et al. 2001). Generally the conversion of plant biomass to carbon storage is estimated using the proportion of carbon in plant dry matter. But conversion rates are not uniform because of differences in tree species composition, ages, and forest stand structure, Therefore, conversion rates for each vegetation type are not always available and global exchange rates of 0.45 and 0.50 are frequently used (Karjalainen 1996). Forest vegetation carbon storage in this study was obtained using a conversion rate of 0.5. Calculation of carbon storage in the forest vegetation excludes the carbon storage in shrubs, herbs, litter and young plantations of diameters less than 5 cm.

Evaluation of contributing factors to forest vegetation carbon changes

Numerous studies suggest that site quality, tree species and forest age are critical factors determining vegetation carbon sequestration (Castello et al. 1995; Jong et al. 2000). To compare the effect of tree species and age structures on vegetation carbon storage, plots with similar site quality and climate condition but free from human influences were selected. Based on remotely sensed data and available raw data from sampled plots, we selected a total of 137 permanent plots in the province. These plots were limited to the 2003 and 2008 surveys due to inadequacy of raw data before 2003.

Statistical analysis

Data on forest area and carbon storage were analyzed by one-way ANOVA, linear regression analysis and two-tailed *t* test using *SPSS 17.0*. In order to evaluate uncertainty of estimations, analysis of the different error sources was conducted. The main sources of errors include errors with the model itself, input data and model parameters (Raupach et al. 2005; Wang et al. 2009). Input data and model parameters were considered the most important error sources (Böttcher et al. 2008; Larocque et al. 2008). The Monte-Carlo method was applied to calculate the possible effects of the errors associated with input data (inventory of forest area and volume) and regression coefficients used for estimation of dominant tree biomass. It was assumed that the errors in input data and regression coefficients follow the normal distribution. Average biomass and standard deviations were calculated by inputting random biomass data of simulated dominant species 1000 times into the forest volume-biomass conversion model.

Table 3 Forest age classification in Fujian province

Forest types	Age classes					Deadline
	Young	Middle-aged	Premature	Mature	Post- mature	
Cunninghamia lanceolata	I–III 1–15	IV–V 16–25	VI 36–30	VII–VIII 31–41	≥IX ≥41	5
Pinus massoniana	I–II 1–20	III–IV 21–40	V 41–50	VI–VII 51–70	≥VIII ≥71	10
Mixed broad-leaved	I–II 1–20	III–IV 21–40	V 41–50	VI–VII 51–70	≥VIII ≥71	10
Casuarina equisetifolia	I–II 1–10	III 11–15	IV 16–20	V–VI 21–30	≥VII ≥31	5
Eucalyptus spp	I–II 1–10	III 11–15	IV 16–20	V–VI 21–30	≥VII ≥31	5

Results

Dynamics of forest vegetation carbon storage

Figure 3 shows that from 1978 to 2008, total vegetation carbon storage increased from 136.51 to 229.31 Tg C, while the forest area increased from 855.27×10^4 to $1,148.66\times10^4$ ha, and vegetation carbon density increased from 15.96 to 19.96 Mg C/ha. During this period, carbon storage dynamics were different in the different types of forests. Forest area and carbon storage in closed forests accounted for 72.73% and 83.70% of Fujian Province (the total six forest categories) forest area and carbon storage, respectively. Changes in carbon storage in closed forests follow similar patterns to the total vegetation carbon storage in each inventory period. Carbon storage in open forests decreased substantially while that in economic forests and bamboo forests increased (Fig. 4). There was little change in carbon storage in shrub forests, which accounts for a small proportion of the total carbon storage. The carbon storage in non-forestry land (namely trees on the sides of villages, houses, roads and waters bodies) also accounted for a small proportion, but it kept increasing from 1988 to 2008 (Fig. 4). These results confirm that vegetation carbon storage increased with reforestation over the study period, and carbon stored in closed forests had the most influence on total vegetation carbon storage.

Between 1978 and 2008, the average forest vegetation carbon storage was 164.07 Tg C with an average annual increase of 1.74% (Fig. 3). However, during the period between 1978 and 1988, when there was no implementation of afforestation and reforestation programs, carbon storage fell from 136.51 to 132.59 Tg C, with an average annual decrease of 0.29%. Implementation of afforestation and reforestation programs in the period from 1989 to 2008 led to carbon storage increasing from 132.59 to 229.31 Tg C, with an average annual increase of 2.67%. The carbon sequestration for the periods of from 1989 to 1993, from 1994 to 1998, from 1999 to 2003, and from 2004 to 2008 were 20.31, 16.33, 31.30, and 28.77 Tg C, respectively, suggesting that carbon sequestration increased from 1989 to 2008 with the maximum (rate of 15.81%) increase in the period from 1999 to 2003.

The aboveground carbon storage of forests in Fujian Province in 1978 was 136.51 Tg C, which was chosen as the baseline. There was an increase of 79.95×10^4 ha in forest area between 1978 and 1988, but the carbon storage dropped by 2.87%. If there had been no afforestation and reforestation programs, there would have been a decrease of 11.73 Tg C up until 2008. However, compared with the baseline, the vegetation carbon storage in the whole province has increased by 92.80 Tg C, which further suggests that afforestation and reforestation programs have played a positive role in increasing carbon storage in Fujian Province.

The vegetation carbon sequestration potential in Fujian Province

Increases in forest vegetation carbon storage mainly come from plantations and forest growth, while decreases in carbon storage mainly result from forest mortality and deforestation (Zhang et al.

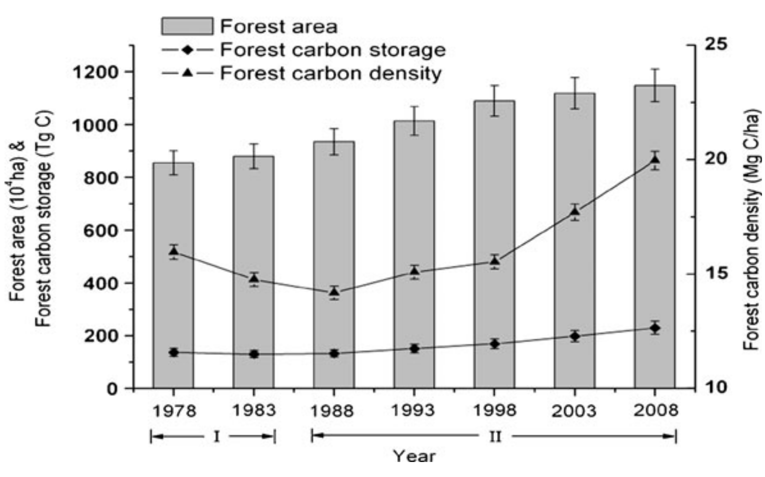


Fig. 3 Changes in forest area, carbon storage and carbon density from 1978 to 2008 (note: carbon dynamics are presented for two periods: I (without implementation of afforestation and reforestation programs) and II (with implementation of afforestation and reforestation programs); carbon storage only includes aboveground carbon storage)

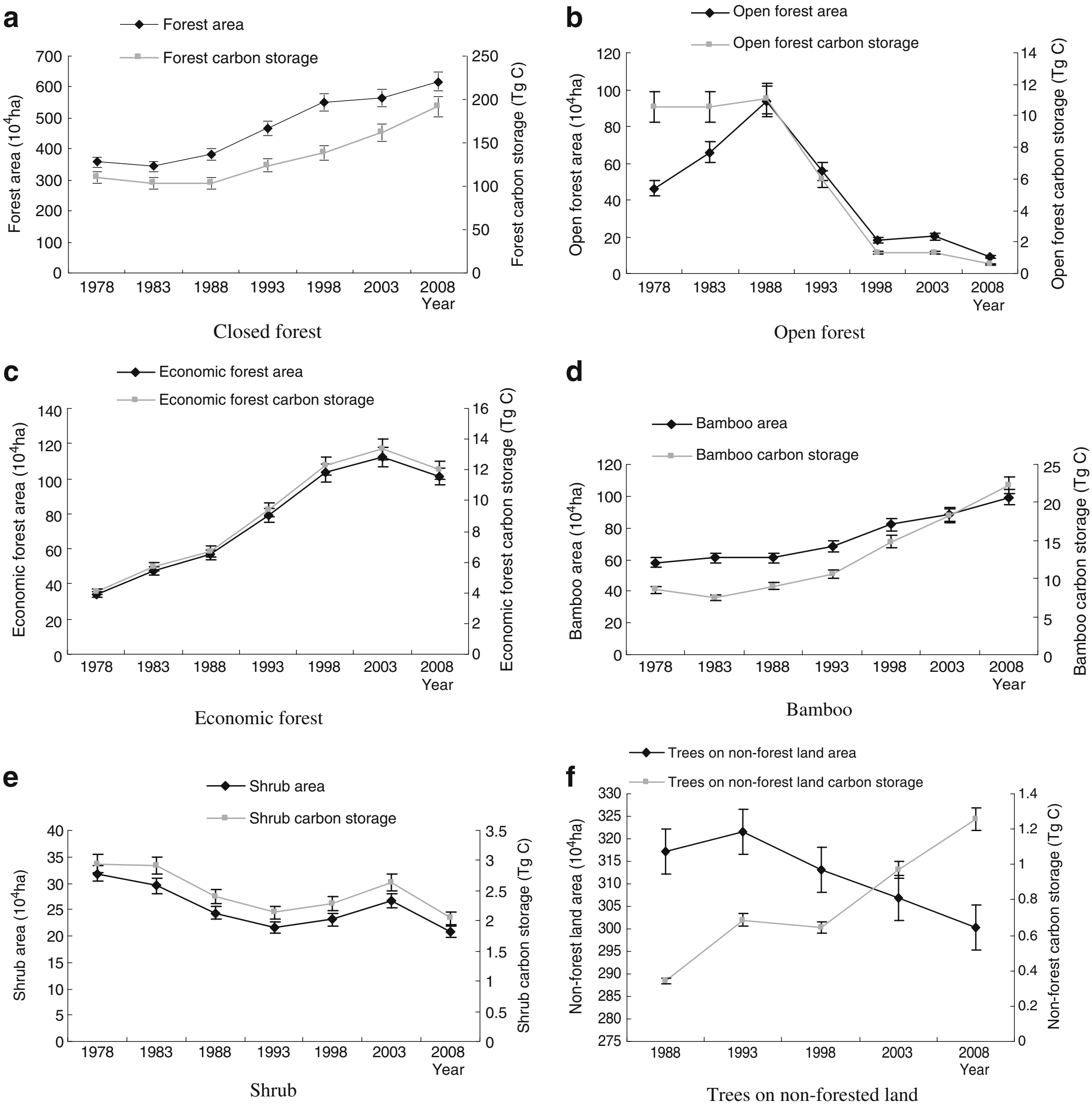
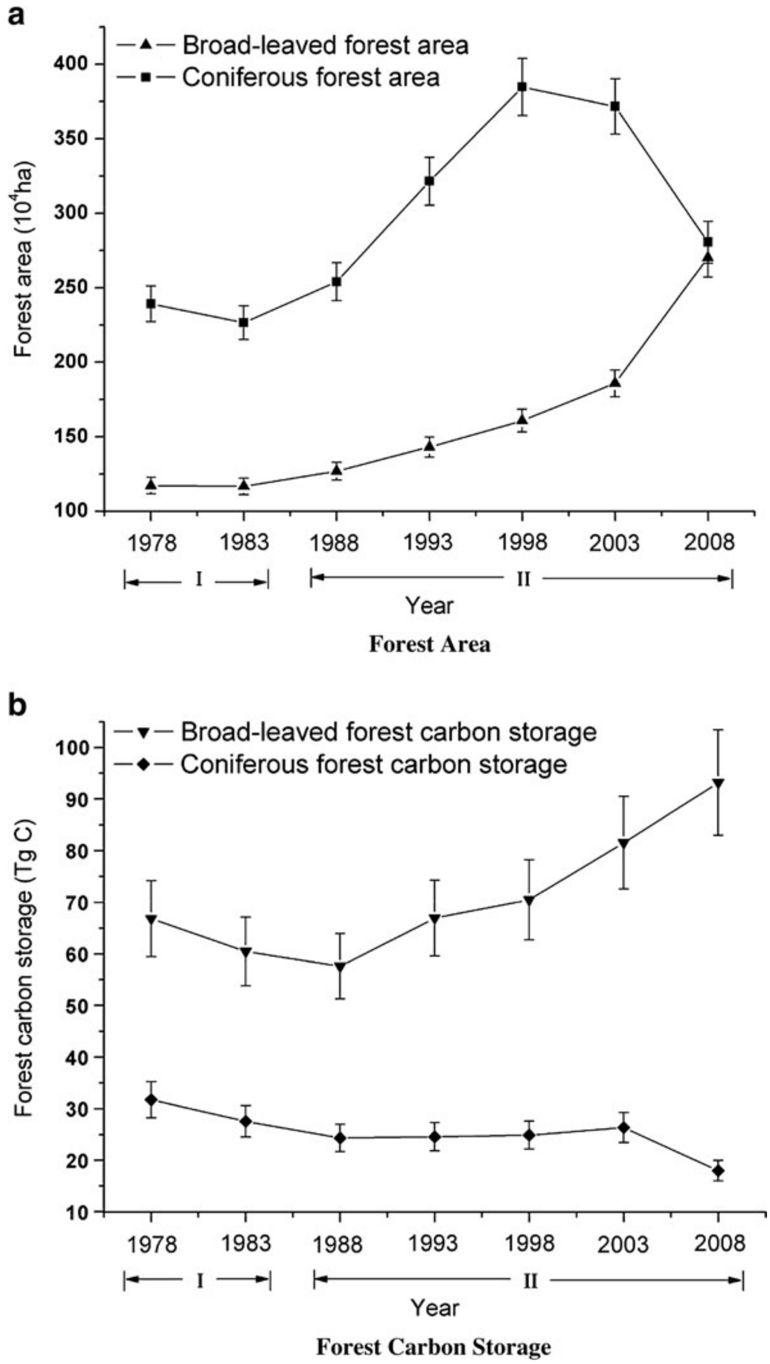


Fig. 4 Dynamics of forest area and forest carbon storage in six types of forests in Fujian province in the period from 1978 to 2008 (**a** closed forests; **b** open forests; **c** economic forests; **d** bamboo forests; **e** shrubs and **f** trees on non-forested land; No information on non-forested land forests is available before 1983; Carbon storage only includes aboveground carbon storage)

2008). The main cause of the drop in carbon storage between 1978 and 1988 was forest harvesting which led to a reduction of forest resources exceeding the total growth. Between 1989 and 2008, forest vegetation carbon storage increased remarkably, mainly due to the measures carried out by the provincial government, including limiting the felling quota, manual hill-closure for natural regeneration, and promoting fast-growing and high-yield plantations. Over the past two decades, the net increase of forest vegetation carbon storage was 96.72 Tg C with an annual rate of carbon sequestration of 4.84 Tg C.

Fig. 5 Forest carbon storage and forest area of coniferous and broad-leaved forests from 1978 to 2008 Note: carbon dynamics are presented for two periods: I (without implementation of afforestation and reforestation programs) and II (with implementation of afforestation and reforestation programs); **a** forest area; **b** forest carbon storage



Assuming the same forest growth and carbon sequestration rates, along with the known time of peak forest growth at 60 years, provides estimated increases in forest vegetation carbon storage of 58.08 Tg C in 2020 and 203.28 Tg C in 2050, as compared with that in 2008.

Effect of tree species on carbon storage

During the period 1978 to 1988, when there was no implementation of afforestation and reforestation programs, the average carbon storage of coniferous and broadleaved forests was 43.95 and 61.63 Tg C, respectively. The average areas were 239.94×10^4 and 121.58×10^4 ha, respectively, and the average carbon density was 18.32 and 50.69 Mg C/ha, respectively. In the period of 1989 to 2008 when afforestation and reforestation programs were implemented, average carbon storage of coniferous and broadleaved forests was 69.41 and 78.04 Tg C, respectively, the average areas were 339.57×10^4 and 196.68×10^4 ha, respectively, and the average carbon density was 20.44 and 39.68 Mg C/ha, respectively. The area ratios of coniferous forests to broadleaved forests decreased from 2.02:1 in 1978 to 0.99:1 in 2008, while their carbon storage ratios changed only slightly from 0.65:1 to 0.62:1 (Fig. 5). The variations of vegetation carbon storage, area and carbon density in broadleaved forests were wider than those in the coniferous forests in both periods suggesting that the afforestation and reforestation programs in Fujian Province had greater impacts on carbon storage in broadleaved forests than in coniferous forests.

Effect of forest age structures on carbon storage

Our results showed that carbon storage mainly exists in middle-aged forests. Over the study period, carbon storage in young and middle-aged forests increased and then decreased, with an opposite trend in mature forests. During the period 1978 to 1988, average carbon storage in young, middle-aged, and mature forests was 24.41, 59.55 and 21.62 Tg C, respectively, average areas were 191.05×10^4, 138.13×10^4, and 32.18×10^4 ha, respectively, and the average carbon density was 12.78, 43.11, and 67.18 Mg C/ha, respectively. In contrast, in the period of 1989 to 2008 young, middle-aged, and mature forests had average carbon storage of 25.29, 80.36 and 48.01 Tg C, respectively, with average areas of 196.82×10^4, 238.60×10^4 and 100.79×10^4 ha, respectively, and the average carbon density was 12.85, 33.68, and 47.63 Mg C/ha, respectively. The area ratios of young, middle-aged and mature forests changed from 4.85:2.98:1 in 1978 to 0.83:1.45:1 in 2008. Accordingly, their carbon storage ratios changed from 0.79:1.90:1 to 0.30:1.05:1 (Fig. 6). Clearly, afforestation and reforestation programs established in Fujian Province had greater effect on carbon storage in middle-aged and mature forests than in young forests.

Effect of forest ownership on carbon storage

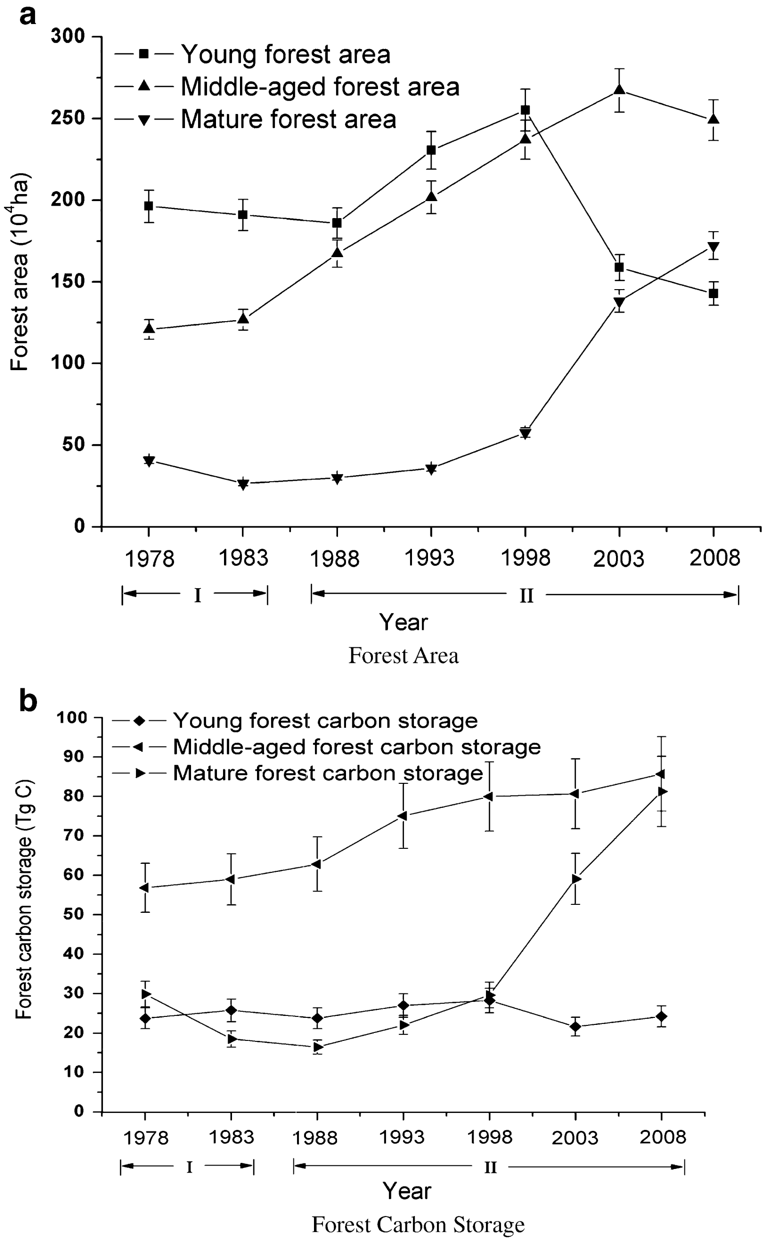
The average carbon storage of state-owned and community-owned forests during the period 1978 to 1988 was 13.87 and 91.71 Tg C, respectively, the average forest areas were 44.16×10^4 and 317.38×10^4 ha, respectively, and the average carbon density was 31.41, and 28.90 Mg C/ha, respectively. In comparison, the average carbon storage of state-owned and community-owned forests in the period of 1989 to 2008 was 28.30 and 109.07 Tg C, respectively, the average forest areas were 76.86×10^4 and 416.94×10^4 ha, respectively, and the average carbon density was 36.82, and 26.16 Mg C/ha, respectively. Vegetation carbon storage and forest areas of state-owned forests increased at average annual rates of 0.67 Tg C and 1.54×10^4 ha, respectively. In contrast, vegetation carbon storage in community-owned forests showed a downward trend at an annual rate of 0.15 Tg C. The community-owned forest area increased in the first period when there was no implementation of afforestation and reforestation programs at an annual rate of 1.08×10^4 ha, but declined at an annual rate of 1.03×10^4 ha during the period 1989 to 2008 when afforestation and reforestation programs were implemented (Fig. 7). These results showed that afforestation and reforestation programs established in Fujian Province had significantly greater effects on the state-owned forests than on the community-owned forests.

Importance of forest area and age in carbon storage

Forest areas in the different categories of tree species, age, and ownership were positively correlated with carbon storage ($P<0.05$) (Table 4). The correlation of broadleaved forest area with carbon storage (R^2=0.951) was higher than that for coniferous forest area (R^2=0.635), while the correlation of mature forest area (R^2=0.976) with carbon storage was higher than those for middle-aged forests (R^2=0.935) and young forests (R^2=0.696). Areas of state-owned forest showed a higher correlation with carbon storage (R^2=0.992) than did community-owned forest (R^2=0.745).

Table 5 shows the effect of tree species and forest age structures on carbon storage under similar site quality and climate conditions based on data from the 137 permanent sample plots. Annual carbon sequestration rates in broadleaved forests of different

Fig. 6 Forest carbon storage and forest area in different forest age groups from 1978 to 2008 Note: Carbon dynamics are presented for two periods: I (without implementation of afforestation and reforestation programs) and II (with implementation of afforestation and reforestation programs); **a** forest area; and **b** forest carbon storage



ages were higher than those in coniferous forests. For young and mature forests, there were significant differences between broadleaved forests and coniferous forests ($P<0.01$), and for middle-aged forests the difference between broadleaved forests and coniferous forests was also significant ($P<0.05$). In addition, the difference in carbon sequestration rates between state-owned and community-owned forests was significant ($P<0.05$).

Uncertainty analysis

The results from uncertainty analysis show that carbon storage errors caused by the model parameters (regression coefficients a, b) constitute the main source of uncertainty in our estimations, accounting for 94.08% to 98.02% of the total error. On the basis of this analysis, further uncertainty analysis was conducted with regression coefficient a, b errors for

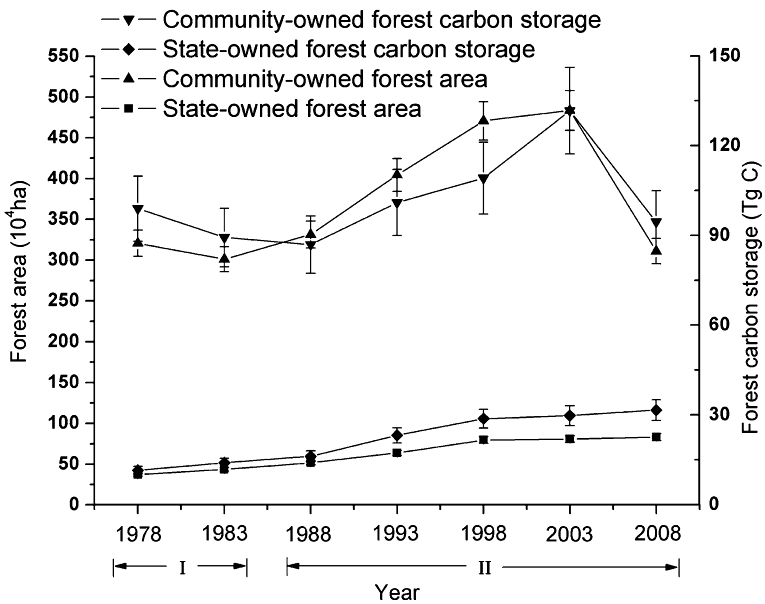


Fig. 7 Forest carbon storage and forest area in state-owned and community-owned forests from 1978 to 2008 Note: carbon dynamics are presented for two periods: I (without implementation of afforestation and reforestation programs) and II (with implementation of afforestation and reforestation programs)

different tree species. The analysis showed that the standard deviation of carbon storage of different tree species accounted for 3.64–4.55% of the total (ranging from 0.02 to 1.51 Tg C). Assuming regression coefficient a, b relative errors were 2%, the average standard deviations of carbon storage for broadleaved and coniferous forests were 0.21 and 0.73 Tg C, respectively (Table 6).

Discussion

The nation-wide Forest Resource Inventory collects systematic, continuous and large-scale field data. This datasetcan be used for determining forest carbon storage and density at a regional or national scale. Many studies have found that middle and high latitude areas in the Northern Hemisphere are huge carbon sinks, but the studies did not explain specific causes for the increased terrestrial carbon sink (Dixon et al. 1994; Houghton 2003; Ajewole 2008). This study has clearly demonstrated that reforestation programs can greatly increase carbon sequestration, and can play a positive role in carbon budgets in forest ecosystems.

Forest carbon sequestration not only depends on forest area, but is also related to forest species and forest ages (McKenney et al. 2004). The effects of afforestation and reforestation programs on forest vegetation carbon sequestration mainly result from

Table 4 Linear regression analyses on the relationship between carbon storage and areas of different forest tree species, forest ages and ownership for seven Chinese Forest Resources Inventory Periods from 1978 to 2008 in Fujian Province

Forest structure		Linear regression equation	SD[a]	*R*	*P*
Tree species	Coniferous	$y = 0.191x + 1.872$	0.065	0.797	0.032
	Broad-leaved	$y = 0.343x + 18.171$	0.035	0.975	<0.01
Forest age	Young	$y = 0.048x + 15.555$	0.014	0.834	0.023
	Middle-aged	$y = 0.191x + 33.992$	0.023	0.967	<0.01
	Mature	$y = 0.408x + 7.587$	0.028	0.988	<0.01
Forest ownership	State-owned	$y = 0.431x - 4.987$	0.016	0.996	<0.01
	Community-owned	$y = 0.169x + 38.404$	0.044	0.863	0.012

[a] Standard deviation (*SD*) given for coefficients error rather than the error for carbon storage estimation; *y* is forest carbon storage (Tg) and *x* is forest area (ha)

Table 5 Analysis of variance for carbon sequestration rates (Mg C yr^{-1}) based on data from 137 permanent plots (the size of plot is 0.0667 ha)

Forest age	Forest type	*N*	Mean	SD	Mean square	*F*	*P*
Young	Coniferous forest	57	0.1199	0.0866	0.0960	10.7900	0.0020
	Broad-leaved forest	11	0.1991	0.1138			
Middle-aged	Coniferous forest	33	0.1068	0.0637	0.0310	6.4710	0.0150
	Broad-leaved forest	13	0.1647	0.0829			
Mature	Coniferous forest	10	0.0939	0.0388	0.0220	16.7720	0.0020
	Broad-leaved forest	13	0.1905	0.0173			

N sample size; *SD* standard deviation; *P* probability

an expanded forest area and increased vegetation carbon density (Zhang et al. 2008). Current rapid economic development and major land use and land cover changes are leading to increased conflict between population growth and demand on natural resources, and impose significant challenges in managing carbon storage through increasing forest area. Increasing carbon density through application of different tree species and age structures can be a realistic and effective strategy (Helmer et al. 2008; Miguel et al. 2006; Ren et al. 2010). The results of this study show significantly greater effects of mature, broadleaved and state-owned forests on carbon storage than young and middle-aged, coniferous and community-owned forests. These results are consistent with the results from Luyssaert et al. (2008). They also suggest an important management direction for Fujian Province in the design of future reforestation programs and further enhancement of vegetation carbon sequestration potentials. In the past, a major focus in designing reforestation programs was on increasing forest area. Future reforestation designs should target more the selection of suitable tree species, management of age structures and implementation of good silvicultural practices.

Table 6 Results of uncertainty analysis on two major source errors of carbon storage estimates in the seven inventories of 1978 to 2008 in Fujian Province (input data SA_1: area and volume and parameter calibration SA_2: *a* and *b* are constants for a forest type) (Tg C)

Year	Carbon (Tg C)	SA		
		SA1	SA2	Total
1978	136.51	0.09	4.47	4.56
1983	129.96	0.10	3.97	4.07
1988	132.59	0.15	4.12	4.27
1993	152.90	0.21	5.06	5.27
1998	169.24	0.28	5.55	5.83
2003	198.01	0.32	6.45	6.77
2008	229.31	0.48	7.64	8.12

In the period of 1989 to 2008, vegetation carbon storage in the whole province increased. In addition to increasing forest areas, changes in forest structures (age and species composition) are the major reason. As shown in Fig. 5, the ratio of broadleaved forests to coniferous forests increased compared with those in the 1978 to 1988 period. The ratio of mature forests to younger forests also increased in the period of 1989 to 2008. These forest structure changes occurred for the following reasons. Firstly, since 2003, Fujian Province has converted a portion of plantation forests to protection forests for the purposes of protecting coastal environment, controlling soil erosion and conserving biodiversity. Secondly, more forested lands have been declared as conservation areas, forest recreation areas and parks, and more trees have been planted in cities and towns. Finally, with rapid economic development, more people (particularly those who live in rural areas) use less wood as fuel, thus more fuel forests are transferred into commercial or protection forests (Benitez et al. 2007; Huang et al. 2009). We expect that forest structures will continue to be adjusted, and more broadleaved forests will be grown in the province. These forest structure changes will lead to increasing vegetation carbon storage.

This study has focused on the effects of afforestation and reforestation programs on vegetation carbon storage without inclusion of soil carbon sequestration. Soil carbon normally comprises about two thirds of the total forest carbon storage (Dixon et al. 1994). In comparison with increases in vegetation carbon storage, many studies have found little influence of afforestation and reforestation upon soil carbon storage (Xu 1995; Viorel et al. 2010). However, the soil carbon bank has a high capacity, and, therefore, small changes in soil carbon storage caused by afforestation and reforestation will likely affect the net carbon sequestration of plantations (Paul et al. 2002). Also, because soil carbon cycling rates are generally low, soil carbon is quite resilient to forest disturbance. Thus, soil carbon storage can be maintained for a long time once it is built up. From this perspective, forest management strategies should be designed to promote more soil carbon storage. For example, slash burning, a common practice in Fujian Province that can decrease decomposition litter and humus as well as increase soil erosion, should be avoided. Another example is to retain suitable loading levels of woody debris after harvesting. Woody debris can be important for soil nutrients, accumulation of humus and consequent accumulation of soil carbon.

Increasing vegetation carbon potentials is largely dependant upon our improved understanding and management. To promote more vegetation carbon storage in Fujian Province to combat climate change impact, more detailed assessments and research are needed in the future. Firstly, assessment of forest change and carbon storage must be done at regional or even local scales in the province as there are large variations in forest species, types, structures and ownerships in different regions, and management strategies are likely to be regional or site-specific (Wang et al. 2009). Secondly, ecosystem-based vegetation carbon models should be applied to evaluate the effects of different forest management practices (rotation length, forest utilization levels, slash burning, fertilization etc.) on carbon sequestration in major forests in Fujian Province (Umeki et al. 2008; Wang et al. 2010). The results from those simulations can be used to improve our management strategies so that vegetation carbon potentials can be maximized (Kimmins et al. 2010). Finally, various other measures should be implemented, such as strictly controlling deforestation, reinforcing macro-control by government, promoting rational allocation of forest land resources, and deepening of forest ownership system reform.

Conclusions

Large-scale reforestation and afforestation programs have resulted in significant growth in vegetation carbon storage over the period 1978 to 2008 in Fujian Province. In spite of the positive role of these forest programs, the vegetation carbon sequestration potentials have not been fully realized at present. Future forest management should focus on the selection of tree species, management of forest stand structures and implementation of sustainable practices so that vegetation carbon sequestration potentials can be maximized.

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