西双版纳农田弃耕后橡胶园的建立对碳的固存作用

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摘要 由于温室气体的大量排放引起的全球气候变暖等环境问题日益严重, 近年来人们开始考虑通过植被和土壤的碳固存, 以缓解大气中 CO_2 浓度的升高速度, 减缓温室效应的影响。有研究表明, 热带原始森林的保护和人工林的建立能有效地固存大气中的碳。但是, 在建立热带种植园和人工林以固存大气 CO_2 的可行性及其碳的固存潜力大小等方面还存在较大争议。云南省西双版纳自治州是我国重要的热带地区之一, 目前橡胶 (*Hevea brasiliensis*) 园的面积为 $1.3 \times 10^5 \text{ hm}^2$, 约占该地区林地面积的 14%。在本研究中, 选择 11 块在弃耕后的农田上建立的橡胶园(定植年限为 3 至 38 年), 初步探讨了橡胶园建立后植被和土壤中碳的固存规律。两个生物量模型(唐建维等的模型和 Brown 模型)的模拟结果显示, 橡胶园建立后植被中生物量的平均增长速率分别为 10.2×10^3 和 $9.4 \times 10^3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, 40 和 100 cm 表层土壤碳的平均固存速率分别为 0.61×10^3 和 $0.72 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, 植被和 100 cm 表层土壤中碳的平均固存速率为 5.82×10^3 和 $5.42 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, 而定植 40 年后植被和 100 cm 表层土壤碳的固存潜力为 232.8×10^3 和 $216.8 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$ 。对两个模型的比较结果显示, 唐建维等的模型生物量计算结果明显高于 Brown 模型, 尤其是在对中幼龄橡胶园生物量估算时更是如此。

关键词 生物量 碳固存 土地利用变化 橡胶园 土壤有机碳

CARBON SEQUESTRATION IN RUBBER TREE PLANTATIONS ESTABLISHED ON FORMER ARABLE LANDS IN XISHUANGBANNA, SW CHINA

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Abstract The ability for vegetation and soil organic matter (SOM) to sequester atmospheric CO_2 has received a lot of attention recently. Two management options being considered for enhancing C sequestration from the atmosphere include tropical forest conservation and establishment of plantations; however, there is still considerable debate regarding the appropriateness of using plantations and the sequestration potential of tropical plantations. There are $1.3 \times 10^5 \text{ hm}^2$ of rubber trees (*Hevea brasiliensis*) plantations in Xishuangbanna, southwest China, which account for approximately 14% of the forest lands in this region. In this study, eleven plantations of different ages were selected to investigate C sequestration in the vegetation and soils following the establishment of rubber tree plantations on former arable lands. The results indicated that the average biomass growth rates of the rubber trees, calculated according to two different biomass growth equations, were 10.2×10^3 and $9.4 \times 10^3 \text{ kg t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$. Soil C stocks in the top 40 cm and 1 m of soil increased at rates of 0.61×10^3 and $0.72 \times 10^3 \text{ kg t C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, respectively. In total, C sequestration was approximately 5.82×10^3 to $5.42 \times 10^3 \text{ kg t C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ in the vegetation and soil as calculated by the two biomass growth models. When comparing the two models, our results showed that the biomass calculated based on the equation of Tang *et al.* was higher than that based on the equation of Brown, especially in young- and middle-aged rubber tree plantations.

Key words Biomass, Carbon sequestration, Land use change, Rubber tree plantation, Soil organic carbon

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Global warming due to greenhouse gases (GHGs), primarily carbon dioxide (CO_2) is one of the most urgent global problems. The uncontrolled emission of GHGs if not addressed properly can cause irreversible and disastrous damage to the whole biosphere. Rising GHGs concentration in the atmosphere could result in a change in energy balance and consequently the world's climate. Among anthropogenic GHGs, CO_2 is the most abundant and is responsible for more than half the radiation associated with the greenhouse effect (Solomon & Srinivasan, 1996). Recently, emphasis has been placed on the need to sequester carbon from atmospheric CO_2 into vegetation and soil organic matter (SOM) because of international concerns about GHGs emissions and global warming.

A cost-efficiency way to reduce the level of CO_2 in the atmosphere is to plant or preserve trees, which absorb C through photosynthesis. Major studies indicate that forestry activity is an important strategy for greenhouse gas reduction and climate change mitigation. Tree is an important route for CO_2 to move from atmospheric gas to solid form (usually expressing as carbon equivalent). This carbon is sequestered, primarily in the new wood and increase soil organic matter that accompanies forest growth. One of the options being considered to mitigate the rise of CO_2 in the atmosphere was tropical forest conservation and restoration (Brown, 1997). This is because of the ability of forests to absorb carbon in the biomass, as well as forest soils. Tropical forests cover 7% of the earth, yet they account for 50% of the aboveground terrestrial carbon pool, and as much as 70% of the global species richness. Between 1850 and 1990, about 108 Pg C had been transferred from forests to the atmosphere as a result of human activity, 2/3 of which was from tropical forests. Over the decade of 1980s the annual flux of carbon resulted from land use changes averaged about $2.0 \text{ Pg C} \cdot \text{a}^{-1}$, almost all of this flux was from tropical regions where deforestation rates averaged approximately $15 \times 10^6 \text{ hm}^2 \cdot \text{a}^{-1}$ (Houghton, 1999). The tropics have the potential to conserve and sequester by far the largest quantity of C (80%), followed by the temperate zone (17%), and the boreal zone (3% only). More than half of the amount in tropical regions was caused by regeneration and deforestation. Plantations and agroforests contributed less than half of the tropical total sink.

Large scale of reforestation to form an additional biosphere C sink to compensate for the input into the atmosphere by the burning of fossil fuels was proposed two decades ago (Breuer, 1979). The resolution of the Kyoto Protocol to include effects of land use and land-use

change in global C budgets has put focus on C sequestration following afforestation of former arable land. Carbon is sequestered in the aggrading biomass of the new forests, but the question remains, to what extent the former arable soils will contribute as sinks for CO_2 . C sequestration is defined simply as "the process of increasing the carbon content of a carbon pool other than the atmosphere". Projected climate change resulting from the increase in atmospheric carbon dioxide (CO_2) has given rise to various strategies designed to store additional carbon in terrestrial ecosystems (IPCC, 1991). Efforts to remove C from the atmosphere and sequester it within terrestrial ecosystems are intended to complement reductions in net energy use accomplished by improving the efficiency of new and existing power plants and by adopting energy conservation plans (Zilberman & Sunding, 2001). Johnsen *et al.* (2001) reported that over the past 40 years forests across the United States had sequestered enough carbon to offset the CO_2 emissions for the US by 25 percent. A large portion of this sequestration is occurring in managed plantations throughout the southern US. Currently, over 32 million acres of land in the southern US is classified as plantations. The majority of these plantations comprised of pine species. This number is expected to reach 60 million acres by the year 2040. Sedjo (1989) examined both tree planting and tree managing schemes. It is estimated that forests in the temperate zone can sequester approximately $6.24 \times 10^3 \text{ kg}$ carbon per hectare per year, and it is predicted that it would take 465 million hectares of temperate forest plantations to offset 2.9 Pg of carbon emissions per year for 30 – 50 years.

A large area of tropical rain forests have been cleared for shifting cultivation and artificial commercial forests due to increasing population pressure and human activities in Xishuangbanna, southwest China since the early of 1950s, which led to serious soil erosion and other environmental problems. Forest cover in this region has reduced from about 50% in the early stage of 1950 to approximate 33.9% in 1975 (Tang *et al.*, 1998a). From the end of 1970s, the local and national government implemented several "Ecological Restoration Projects", which led to reduction of native forest clearing, and increase of afforestation and reforestation. As a result, forest cover had increased to 59% till 1995, although a large proportion of areas are secondary forests and commercial plantations (Tang *et al.*, 1998a). There were $1.3 \times 10^5 \text{ hm}^2$ rubber tree plantations in Xishuangbanna, approximately accounting for approximate 14% of the forest lands, and 6% of the total land area (Xishuangbanna

Bureau of Forestry, 2001). The previous studies conducted in this region were mainly focused on carbon storage of native and secondary forests and the influences of deforestation and reforestation on the biogeochemical cycle of carbon and nitrogen (Tang *et al.*, 1998b; Zhang & Feng, 1997; Sha *et al.*, 1998, 2002; Meng *et al.*, 2001). However, there have been few results about carbon sequestration after secondary forests and plantations established on former arable lands. Therefore, we selected eleven rubber tree plantations with different ages (from 3 to 38 years old) in this region, to investigate carbon sequestration in biomass and soils after establishment of rubber tree plantations. To calculate C sequestration, the following major C pools were measured: biomass, litter, and soil. Tree biomass was computed using the two allometric equations (Brown, 1997; Tang *et al.* 2003).

Therefore, the objectives of this study were: a) to estimate quantitatively biomass and the carbon (C) stocks of rubber tree plantations with different age, b) to model the rate of carbon sequestration in biomass and soils of rubber tree plantations established on former arable lands in Xishuangbanna tropical region, southwest China, 3) to calculate the total carbon quantity sequestered in rubber tree plantation ecosystems in this region.

1 Materials and Methods

1.1 Study site

Xishuangbanna (21°09' to 22°36' N and 99°58' to 101°50'), one of the most important tropical regions in China, covers 1.91×10^4 km², and locates in the southwest of the country. Forest lands are 1.04×10^6 hm², which cover 54.6% of the whole area in Xishuangbanna. The climate of this region, typical north tropical monsoon climate, is characterized by a dry season from November to April and a wet season from May to October. The mean annual temperature and total precipitation in this region are 15.0–21.8 °C and 1 208.0–1 531.9 mm, respectively (Tang *et al.*, 1998a).

Eleven rubber tree plantations with different ages (from 3 to 38 years old) and their reference sites were selected for this study in Mengla county and Jinghong city, Xishuangbanna. The tree density of all the plantations was 450 trees per hectare. The altitude of the 11 plantations ranged from 550 m to 895 m, and the slopes ranged from 5° to 20°. Generally, arable lands near the plantations were selected for the reference sites in this study.

1.2 Calculation of biomass and litter C

1.2.1 Biomass C stocks

In each rubber tree plantation, a 20 m × 20 m plot

and three 0.71 m × 0.71 m sub-quadrats within each plot were established. Diameter at breast height (DBH) and height of all the trees in each plot were measured. The age of plantations was inquired of the plantation owners.

Tree biomass was computed using the following allometric equations:

$$(1) W_t = 0.119\ 021\ 9 \times (D^2 H)^{0.605\ 248\ 3}$$

where: W_t = biomass per tree (kg), D = diameter at breast height (DBH) (cm) measured at 1.3 m above the soil surface and H = height of the tree (cm) (Tang *et al.*, 2003).

$$(2) Y = \exp \{-2.134 + 2.530 \times \ln(D)\}$$

where: Y = biomass per tree (kg) and D = diameter at breast height (DBH) (cm) measured at 1.3 m above the soil surface (Brown, 1997).

Biomass C stocks were captured using the following equation:

$$\text{Biomass C stocks} = W \times \text{fc}$$

Where: W = dry weight of biomass per tree (kg) and $\text{fc} = 0.5 \text{ kg C} \cdot \text{kg}^{-1}$ biomass, which is a standard conversion factor (Houghton, 1995).

1.2.2 C stocks of herb and litter

To determine carbon stocks in herb, all plants (mostly herbaceous plants) were cut at ground level in each sub-quadrat, and weighed. Samples were oven-dried at 80 °C for 48 h and weighed for estimation of total dry weight. To determine litter carbon stocks, litter was collected in each sub-quadrat, and weighed. Samples were oven-dried at 80 °C for 48 h and weighed for estimation of total dry weight.

To measure carbon content of herb and litter, all dry samples were milled to 0.2 mm. C content was determined with H₂SO₄-K₂CrO₇ oxidation method (Nelson & Sommers, 1982). All C contents were measured in triplicate.

1.3 Calculation of soil C

1.3.1 Soil sampling

Soil sampling was done in April and December (during the dry season in this region) of 2001. Three profiles were dug in each plot and its reference site, and three soil samples were taken from each of the following depths: 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm. Soil samples were air-dried, ground with a mortar and pestle, sieved to < 2 mm, and stored for further chemical analysis. To determine the bulk density, 3 undisturbed cores were taken from each depth of the profiles with 100 cm³ cylinders (Culley, 2000).

1.3.2 Chemical analysis

The soil organic carbon (SOC) concentration was measured by $\text{H}_2\text{SO}_4\text{-K}_2\text{CrO}_7$ oxidation method (Nelson & Sommers, 1982). There was no detectable inorganic C in the acidic soils, so that we could regard SOC as total soil carbon. All SOC concentrations were measured in triplicate.

1.3.3 Calculation of soil carbon sequestration

Rate of C sequestration was estimated by comparing soil C stocks under rubber tree plantations with nearby reference sites. Soil carbon density (D , $\text{g C}\cdot\text{m}^{-2}$) was calculated from the following equation: $D = (d)(b)(c)$, where, d is the length of the soil layer (m), b the bulk density of the soil ($\text{g}\cdot\text{cm}^{-3}$), and c the soil C concentration ($\text{g C}\cdot\text{kg}^{-1}$ dry soil). C stocks in the top 20 cm soil was actually the C density of top 20 cm soil, whereas C stocks in the top 40 cm soil was the sum of C density of 0–20 cm and 20–40 cm layers, and C stocks in the top 100 cm soil was the sum of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm layers.

1.4 Statistical analysis

Statistical analysis of soil carbon stocks was performed using analysis of variance (ANOVA) with SPSS 10.0 program. The difference of soil carbon stocks between each plantation and its reference site was analyzed separately. If an F -test proved significant at $p < 0.05$ level then the means of each plot and its reference site were compared by least significant difference (LSD).

To determine C sequestration rate in biomass and soils, we established linear equations using Microsoft Excel. To predict C sequestration potential, we tried to establish sigmoidal biomass growth equation with software SigmaPlot 8.0.

2 Results

2.1 Biomass C stocks and C sequestration rate in rubber tree plantations

Diameter at breast height and mean tree height increased in proportion to age of the plantation. In our study, total biomass of each rubber tree plantation was calculated according to two different allometric biomass growth equations (Tang *et al.* 2003; Brown, 1997). The biomass estimation of each plantation was listed in Table 1. Based on the above two equations, the total biomass of the eleven rubber tree plantations ranged from $6.8 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$ to $340.0 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$ (Tang's equation), and $3.1 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$ to $326.5 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$ (Brown's equation), respectively. According to a standard conversion factor of $0.5 \text{ kg C}\cdot\text{kg}^{-1}$ biomass

(Houghton, 1995), C stocks in biomass of the plantations ranged from $3.4 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}$ to $170.0 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}$, and $1.55 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}$ to $163.25 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}$, respectively.

Fig. 1 showed that the biomass data of each rubber tree plantation calculated according to allometric biomass growth equations of Tang *et al.* (2003) and Brown (1997) fitted to the following sigmoidal curve (in the regression, we used rang of plantation age as x-value):

$$Y = a / (1 + \exp(-(x - x_0) / b))$$

Where: $a = 331.46$, $b = 4.96$, $x_0 = 18.13$, and adjusted $R^2 = 0.9887$ (Fig. 1 a).

Where: $a = 340.34$, $b = 6.02$, $x_0 = 21.88$, and adjusted $R^2 = 0.9891$ (Fig. 1 b).

In accordance with biomass sigmoidal curve a based on biomass data calculated with the equation of Tang *et al.* (2003), the maximum biomass was $331.46 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$, which was slightly lower than the calculated value of the 38-year old plantation ($340.0 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$). However, maximum biomass of curve b was $340.34 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$, which was higher than the calculated value of the 38-year old plantation ($326.5 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$). According to curve a and b, total biomass of 40-year old rubber tree plantation were $327.5 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$, and $324.4 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}$, respectively. And C stocks in biomass were $163.75 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}$ and $162.2 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}$.

In this study, average biomass growth rate and C sequestration rate were determined using linear equations (Fig. 2). According to biomass data calculated with equations of Tang *et al.* (2003) and Brown (1997), biomass growth rates were $10.2 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$ and $9.4 \times 10^3 \text{ kg}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$, respectively. And these two values were very approximate. This indicated that C was sequestered in vegetation at average rate of $5.1 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$ and $4.7 \times 10^3 \text{ kg C}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$ along 38-year chronosequence after rubber tree plantations were established on former arable lands.

2.2 Soil C stocks and C sequestration rate in rubber tree plantations

The establishment and development of rubber tree plantations on former arable lands resulted in C sequestration in soils. However, due to the difference in soil parent materials, altitude, land use history, and so no, soil C stocks in the plantations could not be compared directly. Therefore, we determined soil C increment of each plantation compared to its reference site (adjacent arable lands) firstly, and then compared the C increment of all

Table 1 Site characteristics of eleven rubber tree plantations with different ages (from 3 to 38 years) in Xishuangbanna, Southwest China

Site	Age (a)	Location	Altitude (m)	Aspect	Slope	Soil type	Biomass ($10^3 \text{ kg} \cdot \text{hm}^{-2}$)		Soil C stocks ($\times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$) (cm)		
							Biomass-1	Biomass-2	0–20	0–40	0–100
Guanlei	3	21°42'N, 101°15'E	895	Northeast	5°	Latosols	6.8	3.1	43.8	73.7	133.4
Menglun	3	21°55'N, 101°15'E	750	South	5°	Latosols	7.4	3.6	46.8	86.2	179.0
Daka	4	21°53'N, 101°14'E	750	Southeast	15°	Latosols	9.6	5.8	55.8	92.6	147.7
Jinghong	6	21°43'N, 100°44'E	530	South	5°	Latosols	24.5	16.1	45.5	91.5	176.9
Guanlei	7	21°42'N, 101°15'E	870	Northeast	10°	Latosols	34.2	24.5	42.3	84.2	154.9
Menglun	11	21°54'N, 101°16'E	600	East	5°	Latosols	63.8	48.8	46.1	84.9	170.8
Chengzi	16	21°55'N, 101°14'E	580	East	20°	Latosols	124.8	95.0	34.4	63.4	126.4
Menglun	16	21°53'N, 101°19'E	650	West	10°	Latosols	140.5	106.1	37.2	62.1	112.5
Mengla	21	21°33'N, 101°34'E	710	Northeast	15°	Latosols	222.6	165.1	51.8	96.9	202.5
Mengxing	28	21°55'N, 101°17'E	550	West	15°	Latosols	267.3	232.2	35.2	60.0	111.4
Jinghong	38	21°51'N, 100°22'E	800	Southeast	10°	Latosols	340.0	326.5	37.9	73.5	142.5

Biomass-1, and Biomass-2 were biomass calculated according to two allometric equations (Tang *et al.* 2003; Brown, 1997), respectively. Latosols were called Oxisols or Ultisols according to the USA soil taxonomy

Fig.1 Relationship of biomass and age of rubber tree plantations in Xishuangbanna, Southwest China

The lines denoted regression by sigmoidal curve. Biomass data in curve a, and b were calculated according to allometric biomass growth equations of Tang *et al.* (2003) and Brown (1997)

the plantations.

C stocks of the rubber tree plantations in 20, 40 cm, and 1 m topsoils ranged from $34.4 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$ (16-year plantation) to $55.8 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$ (4-year plantation), $60.0 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$ (28-year plantation) to $96.9 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$ (21-year plantation), and $111.4 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$ (28-year plantation) to $202.5 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2}$ (21-year plantation), respectively. The differences in soil C stocks among the 11 plantations were significant. And the stocks in 40 cm topsoils exceeded approximately half of those in 1 m topsoils in the 11 plantations (Table 1).

In this study, we measured soil C sequestration rate with linear equations. Fig. 3 indicated that C increment of 40 cm and 1 m topsoils in rubber tree plantations was

significantly linearly correlated to age of the plantations ($R^2 = 0.866$, $R^2 = 0.9024$). Along the 38-year chronosequence, C sequestration rates in 40 cm and 1 m topsoils were $0.61 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ and $0.72 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, respectively. This indicated that C sequestration in soils was much lower than that in vegetations, and also suggested it was a long term to sequester C in soils through afforestation.

3 Discussions

3.1 Carbon sequestration in biomass of plantations

The establishment of tropical plantations can result in a net increase in C stored in the terrestrial biosphere including vegetation and soil. However, biomass accumulation rates in tropical secondary forests and plantations

Fig.2 Linear relationship between biomass and age of rubber tree plantations in Xishuangbanna, Southwest China
Biomass data in a and b were calculated according to allometric biomass growth equations of Tang *et al.* (2003) and Brown (1997)

Fig.3 Relationship between soil carbon increment and age of rubber tree plantations in Xishuangbanna, Southwest China

are influenced by many factors, such as location, precipitation, tree species, manage practices. Vitousek (1991) estimated that the potential for tropical plantations to sequester C ranged from $0.8 \times 10^3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ to $24 \times 10^3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ depending on location and the stand age. In tropical Xishuangbanna, average biomass growth rate of natural secondary forests was about $2 \times 10^3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ to $5 \times 10^3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ (Shi *et al.*, 2002; Tang *et al.*, 1998b). However, biomass growth rates of artificial tropical rainforests were much higher (about $10 \times 10^3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) than that of the plantations (Tang *et al.*, 2003). Our results showed that biomass growth rates of rubber tree plantations were much higher than that of natural secondary forests, but very near those of artificial rainforests.

While tropical plantations do not lead to an appreciable sequestration of C in long lived forest products, their establishment does lead to a net increase in the C stored in the tropical terrestrial biosphere. Plantations are generally established on previously degraded and fallow

forestlands that have a relatively low C content (Winjum & Schroeder, 1997). For plantations established in the dry tropical zone, however, it was assumed that plantation biomass at maturity is close to that of the natural dry forest. Although this percentage is highly variable among plantation locations and practices, it does give evidence of an appreciable amount of C sequestration associating with this type of forestry management practice. In our study, biomass of mature rubber tree plantation was about $340 \times 10^3 \text{ kg} \cdot \text{hm}^{-2}$, while that of primary tropical wet seasonal rainforest in this region was $692 \times 10^3 \text{ kg} \cdot \text{hm}^{-2}$ (Zheng *et al.*, 2000), which meant that C pools of the plantation were almost half of the primary rainforest. The rubber tree plantations tend to contain well-spaced trees with little or no understory, and tree density is much lower than natural forests. This lack of structural complexity results in a significant difference between the biomass of the plantations and that of natural tropical wet rainforest. The second factor that often reduces C sequestration in plantation is the plantation harvest. Sequestered C can go

into long-term storage if the harvest is converted to permanent wood products, return to the atmosphere rapidly if the plantation serves as a fuelwood/firewood lot, or decay on some moderate time period if the wood is used for disposable products such as paper. Schroeder (1993) demonstrated that if all sequestered C was immediately returned to the atmosphere, and the woodlot replanted, then the mean C storage of a plantation was 0.5 time of the C storage at harvest.

The amount of C sequestered over time is a more meaningful value than overall potential sequestration, however, it is more difficult to calculate. The great difficulty with a dynamic calculation is that the rate of C accumulation is a highly uncertain parameter. Many factors can influence biomass accumulation rate, and C does not increase linearly. There is significant disagreement in the literatures about the functional form of C accumulation over time. As in most literatures, we supposed that the amount of C sequestered in biomass increased linearly with time in order to simplify calculations when we estimated C sequestration rate.

3.2 Carbon accumulation in soils after establishment of plantations

Carbon sequestration in soils was more complicated than that in vegetations. C sequestration rate in soils is affected by many factors such as vegetation type, temperature, precipitation, soil type, parent materials, and land use history that influence vegetation carbon accumulations. Compared with C stored in aboveground biomass that accounts for the largest percent of the sequestered C within a forest ecosystem, soil C is expensive to monitor and measure, and it is also highly variable depending on stand conditions. So, it is more difficult to calculate carbon sequestration in soils than biomass. As C accumulation in biomass, actually, the amount of soil C in plantations does not increase with time linearly. To simplify the calculation, we also estimated the rate of soil C accumulation with linear equation.

Compared to vegetation, C sequestration rate is much lower in soils in a short- and medium-term. Within this short time span, C sequestration mainly occurs in the biomass of trees while mineral soil C storage has no much increase. Lugo *et al.* (1993) reported that rate of soil C increment ranged from $0.3 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ to $2 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ in the tropics. Garten's result (2002) indicated that the rates of C accumulation in surface (0–40 cm) mineral soils under recently established tree plantations in Tennessee and South Carolina (USA) were $40 \text{ g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ to $170 \text{ g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ (i. e. $0.4 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ to $1.7 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$). In our study, C sequestration rate ($0.72 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) in 1 m topsoils was proximately 14% of

that in biomass ($5.1 \times 10^3 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$). However, the process of soil C accumulation is much longer than C sequestration in biomass, which may go on even for centuries. In a long term, C sequestration in soils could be a large proportion of C accumulated in terrestrial biosphere, and nutrient-rich soils may even become a greater C sink than biomass.

C accumulation mainly occurred in topsoils after tropical plantations were established, at least in the early stage. In our study, the average rate of soil C accumulation in rubber tree plantations in 40 cm topsoils was slightly higher than 80% of that of 1 m topsoils during the 38-year period. Contrarily, the conversion of forests to arable land also mainly reduced C content of topsoils. All these suggested that land use changes mainly influenced C dynamics of topsoils, and less affected deep layers.

Over all, management for C sequestration in the tropics means increasing the amount of C stored in vegetation (living above and below ground biomass), dead organic matter and soil (litter, dead wood, and mineral soil). Increasing the C pool in existing forests can be accomplished by silvicultural treatments, protecting secondary forests and other degraded forests whose biomass and soil C densities are less than their maximum value and allowing them to sequester C by natural or artificial regeneration, and to establish plantations on non-forested lands or increase the tree cover on agricultural or pasture lands (agroforestry) for environmental protection and local needs.

Carbon sequestration may take place over a period of several decades to centuries or so depending upon the present age-class of forests, the attainable maximum C density, forest type, species selection, and latitudinal zone. Establishment of plantations is less environmentally and socially desirable under many situations, especially on degraded lands, it is generally the only option. Such plantations can increase local biodiversity through reestablishment of native species in the understory when they are established on highly degraded lands and are subject to no further management (Lugo *et al.* 1993; Allen *et al.* 1995). These forests can then contribute to the development goals of national forest sectors. Furthermore, if more native forests are to be protected and/or harvesting levels reduced, plantation establishment may become more necessary to offset wood reductions.

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