Carbon Stocks across a Fifty Year Chronosequence of Rubber Plantations in Tropical China

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Abstract

Transition from forest-to-rubber (*Hevea brasiliensis*) plantation has occurred in tropical China for decades. Rubber has been planted in 1 million ha to provide raw materials to the rubber industry. The role of various-aged rubber plantations in C sequestration remains unclear. We examined C accumulation including latex C in five different aged stands (7-, 13-, 19-, 25- and 47-year-old), as well as C distribution in soil. The total biomass C stock (TBC) with above- and belowground and latex was age-dependent. Around 68% of the C was stored in aboveground biomass irrespective of age. The average net primary productivity (NPP) amounted for 6.2 Mg ha\(^{-1}\) yr\(^{-1}\) was not related to stand age. Hereinto, NPP\(_{\text{latex}}\) contributed to approximately 18% of C sequestration. Soil organic carbon (SOC) stock in the entire 100 cm depth remained relatively stable, but it lost about 16.8 Mg ha\(^{-1}\) with stand age. The total ecosystem C stock increased obviously with stand age, averaging 159.6, 174.4, 229.6, 238.1 and 291.9 Mg ha\(^{-1}\), respectively, of which more than 45% was stored in the soil. However, biomass would become the major C sink rather than soil over a 50-year life expectancy of rubber trees. Linear regression showed that in the long term (> 25 years) C stock for rubber plantation is comparable to or slightly higher than a baseline value of 230.4 Mg ha\(^{-1}\) for tropical forest in China (Zhou et al. 2000). This suggests that rubber plantation can be considered as alternative land use without affecting C storage in the forest ecosystem. In addition to the potential C gains, a full set of ecosystem and economic properties have to be quantified in order to assess the trade-offs associated with forest-to-rubber transition.

**Keywords:** rubber; chronosequence; net primary productivity; latex yield; soil organic carbon

Introduction

Increasing carbon dioxide (CO\(_2\)) concentration in the atmosphere resulting from climate change can result in adverse effects to humankind. Forests are a critical component of the terrestrial ecosystem that play a significant role in regulating the global C cycle by serving as a C sink, and thereby potentially mitigating future impacts of climate change (Cheng et al. 2015). Tropical forests represent about half of the global forest area and are believed to be the largest C reservoir of terrestrial biota (Nogueira et al. 2015). These forests hold 470 Pg C in live biomass, debris and soil organic matter, which is approximately 55% of the total C stored in the world’s forests (Pan et al. 2011). Large areas of naturally regenerated tropical forests
have been lost due to changes in land use systems, which lost around 1.4 Pg C yr\(^{-1}\) to atmosphere during 1990–2010 (~15% of global anthropogenic CO\(_2\) emissions) (Hansen et al. 2013). In order to combat global warming and reduce CO\(_2\) emissions from land-use transition, especially due to deforestation and forest degradation, accurate and reliable estimates of C sequestration in various forest ecosystems are needed (Fox et al. 2014).

Rubber tree (\textit{Hevea brasiliensis}) is a perennial cash crop that provides a variety of raw materials to the rubber industry. During the past decades, state-owned farms and particularly smallholder farmers have gained unprecedented wealth due to the rising global rubber prices and the sustainability of government subsidies, i.e. the latex return reached approximately 36,000 yuan ha\(^{-1}\) or 13,000 yuan per person in Xishuangbanna in 2010 (Zhang et al. 2015). Accordingly, large areas of forests have been converted into rubber plantations in the tropics, resulting in major alteration in ecosystem C dynamics due to deforestation and soil erosion (Li et al. 2008; van Straaten et al. 2015). Presently, rubber plantations cover an area of 10 million ha in southeast Asia, out of which 1 million ha is in tropical China. However, the rubber-based incomes are decreasing with the risk of price fluctuation, while selling stumpage would likely raise only a fraction of that when rubber trees complete their economic lifespans (Zhang et al. 2015). To evaluate the trade-offs between ecological system and economic functions, rubber transitions have been the subject of considerable study (de Blécourt et al. 2013; Fox et al. 2014; Kotowska et al. 2015). Their morphological and physio-biochemical traits and soil properties in which they are planted have also been studied (de Blécourt et al. 2014; Kobayashi et al. 2014). However, information on the C sequestration including latex C of rubber plantations is still lacking, particularly in tropical China. Given the expansion of area under rubber plantation in tropical China and the potential expansion rates in the future, a deeper understanding of C sequestration in rubber plantations ecosystem is needed on the part of policymakers, managers, researchers and other groups of scientific community.

C sequestration in forest ecosystem is affected by stand age, topography, climate, soil type, tree species, and management regime (Uri et al. 2012; Li et al. 2015). It has been known that the C stored in tree biomass increases with stand age, the trend may be different for the mineral soil C storage (Yang et al. 2011; de Blécourt et al. 2014; Khasanah et al. 2015).
Specifically, some authors have revealed enhanced biomass C in rubber plantations with stand age, ranging from 1.4 to 6.7 Mg ha$^{-1}$ yr$^{-1}$ (Dey 2005; Yang et al. 2005; Wauters et al. 2008; Saengruksawong et al. 201), but these results excluded an important C component that is stored in latex. Meanwhile, whether net primary productivity (NPP) is related to stand age is still not clear, because Kotowska et al. (2015) observed that no obvious correlation between total biomass C and NPP when including latex yield in NPP. On the other hand, soil C pool might be independent of rubber age sequence, for example, a significant increase in soil organic C (SOC) stock (1.13 Mg ha$^{-1}$ yr$^{-1}$) of rubber plantations during 11 years (Maggiotto et al. 2014), while forest-to-rubber transition resulted in losses of SOC stock by an average of 37.4 Mg ha$^{-1}$ in the entire 1.2 m depth over a time period of 46 years (de Blécourt et al. 2013).

Therefore, our objectives were to: i) quantify above- and belowground biomass C as well as latex C in five different aged (7-, 13-, 19-, 25- and 47-year-old) rubber plantation and; ii) relate SOC storage with increasing stand age. We hypothesized that i) rubber plantation NPP including latex yield will not increase with stand age and, ii) SOC stock will not be affected by rubber plantation.

Materials and Methods

Study site and plot establishment

The study site was located in Mengla County of Xishuangbanna, southwest China (21°09′–22°23′ N, 101°05′–101°50′ E), which borders Myanmar and Laos on the source of the Mekong River. The region has a typical tropical monsoon climate with a rainy season (May–October) and a dry season (November–April). The mean annual rainfall of this area is 1550 mm, out of which 83% occurs in the rainy season and 17% in the dry season (Fig 1). Mean annual evapotranspiration is about 1200 mm. Average relative air humidity ranges from 76 to 89%. Mean annual air temperature is 21.5 °C and minimum and maximum temperatures are 1 and 41 °C, respectively. Temperature often exceeds 38 °C during March and April when the relative humidity is below 40%. The average annual number of sunshine hours is 1800 h with 170 foggy days a year. The soil developed from purple sandstone belongs to Ferralic Cambisol (FAO) (Cao et al. 2006).

Five adjacent rubber plantations with different stand ages were selected based on similar
topography, management practices, environmental conditions and previous vegetation composition (dominated by *Millettia* sp, *Syzygium* sp, *Castanopsis indica* and *Phoebe lanceolata*) in January 2009. The rotation period for rubber plantation is about 40 years in this region due to high mortality caused by pests and disease (Nizami et al. 2014). We identified a chronosequence of rubber stands that were 7, 13, 19, 25 and 47 years of ages. Tapping of rubber trees started at the age of 7 years, and also tapping is underway in 47-year-old stand. All five stands were located within an approximately 10 km radius of each other. Three sampling plots (25 × 40 m) were randomly established in each stand. Within each plot, diameter at breast height (1.3 m, DBH) and height for individual trees were measured using a diameter tape and a Haglöf Vertex clinometer, respectively. Topographical features of each plot, including elevation, slope and aspect, were also recorded (Table 1).

**Field sampling and measurements**

On the basis of the DBH and height measurements in the sampling plots, we selected and harvested six standard trees from different diameter classes in each of the five stands for biomass measurements (30 trees in total). The aboveground portions of the standard trees were divided into 5 cm sections for measurement. We measured the fresh weights of stems, branches and foliage in situ. The belowground portions were obtained by total excavation of the standard trees, extending radially out from the trunk and downwards to bed rock until no more roots were visible. We measured the fresh weights of root collars, stump roots, thick roots (*D* ≥ 2 cm), small roots (0.5 ≤ *D* < 2 cm) and fine roots (*D* < 0.5 cm) in situ. Organ samples (500 g) of every component in each standard tree were collected, and then oven-dried at 70 °C to a constant weight to calculate the ratio of fresh weight to dry biomass. We built regression models for the different organs to evaluate tree biomass (*n* = 30), and the models can be obtained in our previous work (Tang et al. 2009).

Latex was collected three times a month from the onset of tapping in May 2009 and extended about 7 months. The latex production was recorded through weighing of the fresh material separately for all trees of each plot. The dry weight was measured after oven-drying representative subsamples of latex (six collecting bottles) at 70 °C to a constant weight. Meanwhile, monthly tapping times were also recorded. Then, a model (*y* = −0.002*x*² + 0.089*x* + 0.584; *P* < 0.05) was fitted using annual yield (*y*, t ha⁻¹ yr⁻¹) and stand age (*x*). The total
production during the whole tapping ages was calculated by accumulating consecutive annual yield.

Litter, including leaves, twigs ($D < 2$ cm), flowers/fruits and miscellaneous litter component, were collected every month between January 2009 and December 2009 using 10 litter traps ($1 \times 1$ m) that were randomly distributed in each sampling plot. Litter samples were oven-dried at 70 °C to a constant weight to determine the ratio of fresh weight to dry biomass. Plant biomass in the shrub and herbaceous layers was negligible or practically missing due to regular removal by local farmers, except for their litter, and has thus not been investigated.

Three soil profiles in each plot were dug to a depth of 100 cm, and the samples were taken from six depths (0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm) using a soil corer (5 cm inner diameter). Soil samples from the same depth in the same plot were mixed in equal volume proportions and air-dried at room temperature. Bulk density for each soil depth was determined by collecting samples from a stainless steel cylinder (100 cm$^3$) and oven drying the soil core at 105 °C for constant weight. Bulk density was calculated by dividing the mass of oven-dried soil by the volume of the core. Three soil samples were taken from every depth.

For analysis of C concentration, biomass samples were ground and passed through a 1 mm sieve. Mineral soil samples were sieved through a 0.149 mm sieve before chemical analysis. The C concentrations of tree, latex and soil samples were measured by a dry combustion method with a vario MAX CNS elemental analyzer (Elementar, Germany). The tree, latex and litter C stocks (Mg ha$^{-1}$) were calculated by multiplying C concentration by dry biomass (t ha$^{-1}$). The SOC stock (Mg ha$^{-1}$) was calculated by multiplying C concentration by bulk density and thickness of the soil layer with a correction for stone content.

**Statistical analysis**

One-way ANOVA following Tukey HSD test was used to test the differences in biomass production, C concentration and C stocks in different components affected by stand age. Linear regression was applied to check the relationship between C stocks in different components and stand age. The software SPSS 13.0 (SPSS Inc. Chicago, USA) was employed for all statistical analyses at a significance level of 0.05.

**Results**
Biomass C concentration and stock

The C concentration varied substantially among different parts of rubber trees (Fig 2). C concentration of all tree components in the 19-year-old stand was always lower than that in all other stands (Fig 2a). Across all age groups, foliage had the highest C concentration (51.2 ± 0.4%), while roots had the lowest value (46.7 ± 0.4%). The latex C concentration (84.7 ± 0.8%) showed no difference among stand ages (Fig 2b). A significant difference in litter C concentration was only observed between the 7- and 13-year-old stands (Fig 2c). For root components, average C concentration declined in the following order: root collar > stump root > thick root > small root > fine root (Fig 2d).

The total biomass (TB) including above- (AGB) and belowground (BGB) components and latex yield increased significantly with stand age (Table 2). AGB was the largest component of C storage in biomass (68.3 ± 1.0%), followed by latex yield (17.3 ± 2.7%) and BGB (14.3 ± 2.0%) across all age groups. However, the proportion of AGBC/TBC was not related to stand age ($r = 0.10, P = 0.26$), but a positive correlation in latex C/TBC ($r = 0.70, P < 0.01$) and a negative correlation in BGBC/TBC ($r = −0.88, P < 0.001$) could be observed, respectively. The BGBC/AGBC ratio significantly decreased with stand age, ranging from 0.30 in the 7-year-old stand to 0.13 in the 47-year-old stand.

Biomass NPP and associated C sequestration

The biomass NPP and associated C sequestration of various components generally increased first and then decreased with stand age, with the higher values between the 19- and 25-year-old stands, except NPPlitter (Table 3). Across all age groups, more than 75% of C was sequestrated in aboveground tree and litter. Moreover, around 18% of NPP was attributed to latex yield, while a smaller percentage of NPP was allocated to root production. NPPtotal, whether including latex C or not, was not related to stand age ($r = 0.48, P = 0.41$ or $r = 0.51, P = 0.38$).

SOC concentration and stock

In the top 100 cm of the soil, SOC concentration decreased from 1.2% to 1.0% with stand age. Regardless of stand age, the average SOC concentration declined significantly with soil depth, ranging from 1.6% at 0–20 cm to 0.6% at 80–100 cm. In contrast, Bulk density increased with stand age from 1.32 g cm$^{-3}$ in the 7-year-old stand to 1.41 g cm$^{-3}$ in the
47-year-old stand. Irrespective of stand age, the average bulk density increased with soil depth, ranging from 1.31 g cm\(^{-3}\) at 0–20 cm to 1.39 g cm\(^{-3}\) at 80–100 cm.

The SOC stock in the top 100 cm of soil slightly decreased from 146.0 Mg ha\(^{-1}\) in the 7-year-old stand to 129.1 Mg ha\(^{-1}\) in the 47-year-old stand (Fig 3). Across all age groups, SOC stock decreased rapidly with soil depth, ranging from 41.9 Mg ha\(^{-1}\) at 0–20 cm to 17.5 Mg ha\(^{-1}\) at 80–100 cm. With the exception of the 7-year-old stand, more than 52.5% of SOC was accumulated within the upper 40 cm of soil in each stand. No significant difference in SOC stock between soil depths was observed among the five different ages.

**Ecosystem C stock and its relationship between main components**

The total ecosystem C stock (TEC) increased with stand age, ranging from 159.6 Mg ha\(^{-1}\) in the 7-year-old stand to 291.9 Mg ha\(^{-1}\) in the 47-year-old stand. The contribution from TBC to TEC increased from 8.6% for the 7-year-old stand to 55.1% for the 47-year-old stand (Fig 4). Thereinto, latex C contributed 0.6–13.4% to TEC with stand age. Most of TEC was occupied by SOC rather than TBC. Indeed, 91.4% of TEC in the 7-year-old stand was sequestrated in the top 100 cm of soil. This proportion decreased significantly with stand age, and fell to 44.9% in the 47-year-old stand.

Linear mixed model analysis showed that, C stored in main biomass components was positively correlated with stand age (\(P < 0.01\)), while SOC stock was negatively correlated with age classes (\(P = 0.14\)) (Table 4). The TEC, whether excluding latex C or not, also exhibited a significant positive correlation with stand age (\(P < 0.001\)), which is similar to a comprehensive fitting using previous data.

**Discussion**

**Biomass C accumulation**

Accurate estimation of C stocks in different development stages of plantations is important for assessing their role in regional and global C management. The C concentrations of plantations are closely related to their chemical compositions, and vary with type of tree components (stems, branches, foliage and roots), type of wood (normal, tension or compression), soil conditions, geographical location, and climate (Bert and Danjon 2006). Thus, the component-specific C concentration values are often used when converting biomass to C stocks instead of a standard factor of 50% (Peichl and Arain 2006). The average C
concentration of rubber tree (48.4%) (Fig 2) was higher than that of higher plants (43.6%) (Zheng et al. 2007). The use of 50% therefore could overestimate biomass C stock by as much as 4% in this region. Moreover, the lowest C concentration in the 19-year-old tree is attributed to a highest increment rate rather than soil texture, so maybe the fast growth rate will result in less dense biomass. We also suggest that a general C concentration of 48% can be applied as an alternative to empirical assessments of site-specific values.

The TBC including AGBC, BGBC and latex C of rubber plantations increased markedly with stand age (Table 2). Thereinto, AGB made up the largest proportion of TBC irrespective of stand age, which is consistent with recent findings for tropical trees (Fonseca et al. 2012; Zhang et al. 2014). The BGBC/AGBC ratio decreased with stand age, which is different from other study reporting larger C accumulated in roots over a long time period (105-year-old) (Cao et al. 2012). The highest C increment was 6.4 Mg ha\(^{-1}\) yr\(^{-1}\) between the 13–19 years stands (Table 2), which is associated with the fast growth rates. Rubber plantations grown in potentially dissimilar conditions in Brazil (Wauters et al. 2008; Maggiotto et al. 2014) and Asia ((Dey 2005; Yang et al. 2005; Saengruksawong et al. 2012) have revealed comparable C increment, varying from 1.4 to 6.7 Mg ha\(^{-1}\) yr\(^{-1}\), with highest values occurring between the 10–20 years stands. Also, the largest TBC in the 47-year-old stand was higher than the value of 110.9 Mg ha\(^{-1}\) measured for tropical forest in China (Zhou et al. 2000). These comparisons indicate that rubber plantations can serve as an effective C sink by a rapid rate of biomass C accumulation in the early stages of plantation, although the rate will slow down with stand age.

The C stock of fine roots was age-dependent (Table 2). As a result of abundant water and nutrients in the topsoil, the majority of fine root C was located in the upper 40 cm soil layer (data not shown), which has been reported in several chronosequence studies regardless of tree species (Wang et al. 2013; Zhang et al. 2014). Here, litter C stock increased with stand age. This trend is in line with some chronosequence studies of broad-leaved plantations (Mao et al. 2010; Fonseca et al. 2012), but not with others (Uri et al. 2012; Ming et al. 2014), indicating large between-stand variability. The controversy mainly results from input and decomposition rates of litter that is highly susceptible to disturbances and spatial variation (Pregitzer and Euskirchen 2004; Peichl and Arain 2006). It was also clear that miscellaneous
litter was age-dependent, suggesting the rapid decomposition of litter, particularly leaves. We also found that the C stock of litter in each stand was greater than that of tree foliage, indicating that litter should be considered an essential component in TBC assessment.

Our estimate of NPP$_{\text{total}}$ for rubber plantations, whether excluding latex C or not, did not increase with stand age, supporting the first hypothesis. The average NPP$_{\text{total}}$ amounted for 6.2 Mg ha$^{-1}$ yr$^{-1}$ during the 50 year life time was a little lower than the estimated rates (~7.8 Mg ha$^{-1}$ yr$^{-1}$) reported in past studies (Song et al. 2014; Kotowska et al. 2015). This discrepancy is likely attributed to single stand age (e.g. 16- or 33-year-old) measurement in their studies. However, rubber plantation can be considered having a considerable C sequestration capacity, although these values were significantly lower than the global NPP of 10.9 Mg ha$^{-1}$ yr$^{-1}$ measured for tropical forests (Cleveland et al. 2015). It is worth noting that latex C was more prominent in its contribution to NPP relative to roots (Table 3), which is consistent with the estimation in rubber monoculture of Indonesia by Kotowska et al. (2015), who reported about 20.8–31.3% of NPP was allocated to latex, while a smaller percentage was attributed to leaf and root. It is worth noting that latex yield measured in a given year or estimated from our model does not accurately reflect the rubber productivity of the whole economic life cycle. Therefore, we suggest that a continuous monitoring in latex yield is necessary for accurate estimation of rubber plantation NPP$_{\text{total}}$.

**Soil C stock**

Although soil C generally is expected to decrease due to soil disturbance and aeration in the early decades after plantation establishment (Cao et al. 2012; Ming et al. 2014), some studies suggest that SOC stock is neutral, i.e. neither increases nor decreases with stand age (Peltoniemi et al. 2004; Cheng et al. 2015; Khasanah et al. 2015). This phenomenon may be ascribed to numerous factors, such as land use history, soil properties, tree species, pre-planting disturbance, site management, and human activity, all of which may individually or jointly overshadow the effect of stand age on SOC stock (Peichl and Arain 2006; Uri et al. 2012). We found that no significant correlation between SOC stock and stand age ($r = -0.40$, $P = 0.14$), supporting the second hypothesis. This result might indicate fast organic C turnover in rubber soils. However, about 22.3 Mg ha$^{-1}$ SOC stock has lost over a period of 47 years compared with its amount prior to rubber establishment (151.4 Mg ha$^{-1}$). Similarly, de
Blécourt et al. (2013) found that forest-to-rubber transition resulted in losses of SOC stock of 120 cm (37.4 Mg ha$^{-1}$) over a period of 46 years, which was equal to 19.3% of the initial SOC stock in the secondary forests. In contrast, Maggiotto et al. (2014) found a small, but significant, increase in SOC stock (12.4 Mg ha$^{-1}$) over 11 years of rubber plantations. Over the long run, however, SOC stock trajectory with stand age will tend to be relatively stable and remains an essential part of the C budget of the overall plantation ecosystem.

In addition, SOC in the top soil did not increase with stand age, whereas its stock estimate using a modelling method showed a positive trend (Peltoniemi et al. 2004). Approximately 48.0–57.8% of SOC was found in the top 40 cm soil in all stands (Fig 3), despite the topsoil being vulnerable to human disturbance and natural erosion (Khasanah et al. 2015). Thus, focus on the vertical variability of SOC stock, and protection of the topsoil from loss is very essential for C sequestration (Li et al. 2015). The average SOC stock of 136.0 Mg ha$^{-1}$ within the upper 100 cm in our study was similar to the mean value of 146.2 Mg ha$^{-1}$ obtained from rubber plantations of different ages elsewhere (Yang et al. 2005; Wauters et al. 2008), but higher than a chronosequence of rubber plantations in Thailand (Saengruksawong et al. 2012) and Hainan Island (Zheng et al. 2010), reporting average value of 89.5–96.9 Mg ha$^{-1}$ at the same depth. These results indicate that SOC stock may be largely determined by the site-specific C concentration, and the soil with the low initial SOC concentration will easily increase C sink following transition to rubber and vice versa (van Straaten et al. 2015).

Although SOC stock we observed was much lower than the average value of 193.6 Mg ha$^{-1}$ for Chinese forest ecosystems, it was higher than the 116.5 Mg ha$^{-1}$ measured for tropical forest soil in China (Zhou et al. 2000). Thus, we could speculate that organic matter decomposition and subsequent accumulation in soil C happens faster in our study region compared to the whole tropical forest soil in China due to precipitation surplus or intensive management.

**Ecosystem C stock**

The TEC increased by nearly 82.9% with stand age and reached 291.9 Mg ha$^{-1}$ in the 47-year-old stand, indicating a considerable C sequestration potential in rubber plantations over an approximately 50 year life time. Although this value was higher than the average TEC of 230.4 Mg ha$^{-1}$ for tropical forest in China (Zhou et al. 2000), the 47-year-old rubber trees
are rarely found and the results here are not indicative of the dominant situation. Also, our value was similar to estimation from comprehensive mixed model (313.9 Mg ha\(^{-1}\)) (Table 4). In contrast, Nizami et al. (2014) predicted rubber plantations to be a smaller C sink (186.7 Mg ha\(^{-1}\)) in a 40 years rotation estimated by the CO\(_2\)FIX Model. Another important finding by this study was that although TBC increased over age sequence, SOC stock was relatively stable (Fig 3). However, the contribution of SOC to TEC decreased rapidly with stand age (Fig 4), similar to findings obtained from *Pinus strobus* (Peichl and Arain 2006) and *Cyclobalanopsis glauca* (Zhang et al. 2014) plantations. This pattern did not occur in all plantations because of the differences in the rates of biomass and soil C accumulation among tree species during stand development (Wang et al. 2013; Ming et al. 2014). Uri et al. (2012) found that AGBC will ultimately surpass the C stored in soil of the older stands. We suggest that when considering a 50-year life expectancy, biomass including latex yield or not may become the major C stock of rubber plantations. Therefore, further evidence for ecosystem C pool dependence on stand age will be required, in particular studies with a very long time perspective (> 50 years).

### The implications of rubber plantations on C sequestration

Although forest-to-rubber transition can increase farmers’ income in the short or medium term, more attention should be paid to the implications for C sequestration of the transition, especially transitions with baseline in the two main forest types, degraded and natural (maybe even undisturbed) forests. Firstly, large areas of degraded forest lands with low C stocks could benefit from the establishment of rubber plantations (Fox et al. 2014). For example, biomass C in the five rubber plantation age classes (Table 2) was always higher than that in degraded forest in the same region as reported by our previous work (Tang et al. 1998), indicating a rapid biomass accumulation rate in rubber plantations. Secondly, the consequences of converting natural forests with much higher C stocks, old-growth forest in particular, to rubber have shown to result in large C debts (de Blécourt et al. 2013), because rubber plantations C payback time is about 40 years (Kongsager et al. 2013; Nizami et al. 2014). Under these two scenarios, biomass C has been predicted to increase about 11.8 Tg or lose 4.13 Tg in Xishuangbanna during the next 20 years (Li et al. 2008). Also, we found that rubber plantations could lead to increased C sequestration in the long term (> 25 years).
according to relationship between TEC including latex C and stand age (Table 4), because the value will exceed the average TEC for Chinese tropical forest. As a result, there is no doubt that rubber plantations can be considered as alternative land use without affecting C storage in the forest ecosystem.

There is a big drawback, however, to the large-scale rubber monocultures in the form of reduction in biodiversity, loss of soil and water and an increase in vulnerability to diseases and pests (Fox et al. 2014). More seriously, only about 129.9 Mg C ha\(^{-1}\) in soil is left once rubber plantations are harvested for rotation (40 years). By contrast, rubber agroforestry systems are found to be environmentally-friendly due to their diversity and complexity. For example, leguminous cover crops planted between rubber trees can substantially increase C stock in addition to improving soil fertility (Ziegler et al. 2012). Further studies on ecosystem C stock of rubber plantation should include not only potential ecological issues associated with monocultures but also comparisons to mixed agroforestry systems in general.

Conclusions

In a chronosequence of rubber plantations in tropical China, the TBC with above- and belowground and latex increased markedly with stand age. AGB made up the largest proportion of TBC irrespective of stand age. However, NPP\(_{\text{total}}\), whether including latex C or not, was not related to stand age. NPP\(_{\text{latex}}\) contributed to approximately 18% of C sequestration. The SOC stock in the top 1 m soil was age-independent, and decreased with soil depth for each stand. The TEC averaged 159.6, 174.4, 229.6, 238.1 and 291.9 Mg ha\(^{-1}\), respectively, of which more than 45% was stored in the soil. When considering a 50-year life expectancy of rubber trees, the C accumulated in biomass would exceed soil over age sequence. The results of this investigation indicate that rubber plantations have a potential role in improving the regional C budget in the long term (> 25 years), and thus they should be considered as alternative land use without affecting C storage in the forest ecosystem. We also suggest that further research on ecosystem C pool dependence on stand age in rubber agroforestry systems is needed to fully achieve a “win-win” between environmental and economic benefits in tropical China.

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References:


de Blécourt M, Hänsel VM, Brumme R, Corre MD, Veldkamp E (2014) Soil redistribution by terracing alleviates soil organic carbon losses caused by forest conversion to rubber


Song QH, Tan ZH, Zhang YP, Sha LQ, Deng XB, et al. (2014). Do the rubber plantations in tropical China act as large carbon sinks? iForest 7:42–47.


Fig 1. Mean pattern of the monthly precipitation, temperature and relative humidity in Mengla County observed over a 48-year period (1962–2009).
Fig 2. Carbon concentrations in different biomass components of the 7-, 13-, 19-, 25- and 47-year-old rubber plantations. Means followed by different letters indicate significant differences among stand ages according to Tukey HSD test ($P < 0.05$). Vertical bars show ± S.E.
Fig 3. Soil organic carbon stock in different layers of the 7-, 13-, 19-, 25- and 47-year-old rubber plantations. Means followed by different letters indicate significant differences among stand ages according to Tukey HSD test ($P < 0.05$). Vertical bars show ± S.E.
Fig 4. Percentage distribution of carbon stock in various components of rubber plantation ecosystem of five different ages.
Table 1. Stand and soil characteristics of the 7-, 13-, 19-, 25- and 47-year-old rubber plantations. Values are means ± S.E. Means followed by different letters indicate significant differences among stand ages according to Tukey HSD test ($P < 0.05$).

<table>
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<th>Stand parameter</th>
<th>7-year-old</th>
<th>13-year-old</th>
<th>19-year-old</th>
<th>25-year-old</th>
<th>47-year-old</th>
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<td>101°14'40.1″</td>
<td>101°14'43.5″</td>
<td>101°16'28.9″</td>
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<td>Elevation (m)</td>
<td>580–595</td>
<td>600–620</td>
<td>560–570</td>
<td>570–580</td>
<td>550–570</td>
</tr>
<tr>
<td>Aspect</td>
<td>South-west</td>
<td>South-east</td>
<td>South-east</td>
<td>South-east</td>
<td>South-west</td>
</tr>
<tr>
<td>Planting spacing (m)</td>
<td>2.5 × 6</td>
<td>2.5 × 6</td>
<td>2.5 × 8</td>
<td>2.5 × 8</td>
<td>2.5 × 8</td>
</tr>
<tr>
<td>Average DBH (cm)</td>
<td>9.3 ± 0.7 d</td>
<td>15.5 ± 0.8 c</td>
<td>21.4 ± 1.2 b</td>
<td>24.9 ± 0.7 b</td>
<td>40.4 ± 2.2 a</td>
</tr>
<tr>
<td>Average height (m)</td>
<td>7.3 ± 0.9 c</td>
<td>13.9 ± 1.0 b</td>
<td>16.3 ± 1.2 ab</td>
<td>17.2 ± 0.8 a</td>
<td>21.3 ± 1.1 a</td>
</tr>
<tr>
<td>Density (plants ha⁻¹)</td>
<td>667 ± 31 a</td>
<td>637 ± 26 a</td>
<td>626 ± 21 a</td>
<td>510 ± 23 ab</td>
<td>203 ± 17 b</td>
</tr>
<tr>
<td>Basal area (m² ha⁻¹)</td>
<td>5.1 ± 0.8 c</td>
<td>11.3 ± 1.0 b</td>
<td>21.9 ± 1.8 ab</td>
<td>24.6 ± 0.7 a</td>
<td>29.5 ± 0.9 a</td>
</tr>
<tr>
<td>pH</td>
<td>6.5 ± 0.2 a</td>
<td>6.4 ± 0.1 a</td>
<td>6.0 ± 0.1 a</td>
<td>5.7 ± 0.1 ab</td>
<td>5.4 ± 0.1 b</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>30.3 ± 3.5 a</td>
<td>28.5 ± 2.3 a</td>
<td>32.2 ± 2.0 a</td>
<td>29.1 ± 3.4 a</td>
<td>26.9 ± 2.9 a</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>34.5 ± 2.2 a</td>
<td>33.0 ± 3.7 a</td>
<td>33.8 ± 2.7 a</td>
<td>31.5 ± 0.5 a</td>
<td>28.0 ± 0.7 b</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>35.2 ± 0.4 b</td>
<td>38.5 ± 1.1 ab</td>
<td>34.0 ± 0.2 b</td>
<td>39.4 ± 0.9 a</td>
<td>45.1 ± 1.8 a</td>
</tr>
</tbody>
</table>
Table 2. Above- and belowground biomass and latex yield (t ha\(^{-1}\)) and carbon stock (in brackets Mg C ha\(^{-1}\)) in different components of the 7-, 13-, 19-, 25- and 47-year-old rubber plantations. Values are means ± S.E. Means followed by different letters indicate significant differences among stand ages according to Tukey HSD test (\(P < 0.05\)). AGB: aboveground biomass. BGB: belowground biomass. TB: total biomass.

<table>
<thead>
<tr>
<th>Biomass fraction</th>
<th>7-year-old</th>
<th>13-year-old</th>
<th>19-year-old</th>
<th>25-year-old</th>
<th>47-year-old</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ab. tree</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stem</td>
<td>12.86 ± 1.57 (6.20) c</td>
<td>38.66 ± 1.88 (18.56) c</td>
<td>92.17 ± 6.77 (43.57) b</td>
<td>106.56 ± 9.52 (52.88) b</td>
<td>169.50 ± 16.19 (81.84) a</td>
</tr>
<tr>
<td>Branch</td>
<td>3.63 ± 0.44 (1.77) c</td>
<td>10.74 ± 0.53 (5.15) c</td>
<td>25.29 ± 1.86 (12.00) b</td>
<td>29.15 ± 2.60 (14.48) b</td>
<td>45.54 ± 4.32 (21.87) a</td>
</tr>
<tr>
<td>Foliage</td>
<td>0.75 ± 0.09 (0.39) c</td>
<td>1.87 ± 0.10 (0.95) c</td>
<td>3.88 ± 0.30 (1.94) b</td>
<td>4.32 ± 0.37 (2.24) ab</td>
<td>5.62 ± 0.51 (2.86) a</td>
</tr>
<tr>
<td>Litter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf</td>
<td>2.50 ± 0.09 (1.29) b</td>
<td>3.82 ± 0.20 (1.90) a</td>
<td>4.24 ± 0.30 (2.17) a</td>
<td>3.77 ± 0.06 (1.92) a</td>
<td>4.12 ± 0.05 (2.12) a</td>
</tr>
<tr>
<td>Twig</td>
<td>0.02 ± 0.00 (0.01) c</td>
<td>0.40 ± 0.08 (0.20) b</td>
<td>0.59 ± 0.14 (0.30) ab</td>
<td>0.82 ± 0.02 (0.42) a</td>
<td>0.40 ± 0.04 (0.21) b</td>
</tr>
<tr>
<td>Flower/fruit</td>
<td>0.10 ± 0.01 (0.06) c</td>
<td>0.35 ± 0.07 (0.18) b</td>
<td>0.26 ± 0.07 (0.14) b</td>
<td>0.92 ± 0.01 (0.47) a</td>
<td>0.76 ± 0.10 (0.39) a</td>
</tr>
<tr>
<td>Miscellaneous litter</td>
<td>0.12 ± 0.01 (0.06) c</td>
<td>0.15 ± 0.01 (0.08) c</td>
<td>0.16 ± 0.01 (0.08) bc</td>
<td>0.23 ± 0.01 (0.12) b</td>
<td>0.42 ± 0.03 (0.22) a</td>
</tr>
<tr>
<td>Total litter</td>
<td>2.74 ± 0.12 (1.42) b</td>
<td>4.72 ± 0.36 (2.35) a</td>
<td>5.25 ± 0.53 (2.69) a</td>
<td>5.74 ± 0.08 (2.93) a</td>
<td>5.70 ± 0.21 (2.94) a</td>
</tr>
<tr>
<td>Total AGB</td>
<td>19.98 ± 2.11 (9.78) c</td>
<td>55.99 ± 2.87 (27.01) c</td>
<td>126.59 ± 9.46 (60.20) b</td>
<td>145.77 ± 12.57 (72.53) b</td>
<td>226.36 ± 21.23 (109.51) a</td>
</tr>
<tr>
<td>Root</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root collar</td>
<td>2.41 ± 0.26 (1.16) c</td>
<td>6.13 ± 0.38 (2.91) b</td>
<td>7.21 ± 0.61 (3.38) ab</td>
<td>9.29 ± 0.79 (4.49) a</td>
<td>9.59 ± 0.83 (4.57) a</td>
</tr>
<tr>
<td>Stump root</td>
<td>2.34 ± 0.25 (1.11) c</td>
<td>4.35 ± 0.27 (2.04) b</td>
<td>6.20 ± 0.52 (2.87) a</td>
<td>4.59 ± 0.39 (2.19) b</td>
<td>4.42 ± 0.38 (2.09) b</td>
</tr>
<tr>
<td>Thick root</td>
<td>0.46 ± 0.05 (0.22) c</td>
<td>1.32 ± 0.08 (0.62) c</td>
<td>5.15 ± 0.43 (2.37) b</td>
<td>9.41 ± 0.80 (4.45) a</td>
<td>8.17 ± 0.71 (3.82) a</td>
</tr>
<tr>
<td>NPP fraction</td>
<td>7-year-old</td>
<td>13-year-old</td>
<td>19-year-old</td>
<td>25-year-old</td>
<td>47-year-old</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>NPP_aboveground tree</td>
<td>2.46 ± 0.30 (1.19) c</td>
<td>3.94 ± 0.19 (1.90) bc</td>
<td>6.39 ± 0.47 (3.03) a</td>
<td>5.60 ± 0.50 (2.78) ab</td>
<td>4.69 ± 0.45 (2.27) ab</td>
</tr>
<tr>
<td>NPP_litter</td>
<td>2.74 ± 0.12 (1.42) b</td>
<td>4.72 ± 0.36 (2.35) a</td>
<td>5.25 ± 0.53 (2.69) a</td>
<td>5.74 ± 0.08 (2.93) a</td>
<td>5.70 ± 0.21 (2.94) a</td>
</tr>
<tr>
<td>NPP_root</td>
<td>0.87 ± 0.09 (0.42) bc</td>
<td>1.04 ± 0.06 (0.49) ab</td>
<td>1.33 ± 0.11 (0.62) a</td>
<td>1.10 ± 0.09 (0.52) ab</td>
<td>0.66 ± 0.05 (0.31) c</td>
</tr>
<tr>
<td>NPP_latex</td>
<td>1.10 ± 0.00 (0.91) c</td>
<td>1.25 ± 0.01 (1.06) b</td>
<td>1.35 ± 0.02 (1.14) a</td>
<td>1.39 ± 0.03 (1.19) a</td>
<td>1.12 ± 0.02 (0.94) c</td>
</tr>
<tr>
<td>NPP_total</td>
<td>7.17 ± 0.51 (3.94) b</td>
<td>10.95 ± 0.62 (5.79) a</td>
<td>14.32 ± 1.11 (7.48) a</td>
<td>13.83 ± 0.67 (7.42) a</td>
<td>12.18 ± 0.71 (6.46) a</td>
</tr>
</tbody>
</table>

Table 3. Net primary productivity (NPP) (t ha\(^{-1}\) yr\(^{-1}\)) and carbon stock (in brackets Mg C ha\(^{-1}\) yr\(^{-1}\)) in different components of the 7-, 13-, 19-, 25- and 47-year-old rubber plantations. Values are means ± S.E. Means followed by different letters indicate significant differences among stand ages according to Tukey HSD test (\(P < 0.05\)).
Table 4. The linear relationship between carbon stored in different components of rubber plantation ecosystem and stand age. * Data of total ecosystem C stock (comprehensive) were collected from previous studies irrespective of management practices, soil texture and environmental conditions (Dey 2005; Yang et al. 2005; Cotta et al. 2006; Cheng et al. 2007; Sha 2008; Wauters et al. 2008; Peng 2010; Zheng et al. 2010; Egbe et al. 2012; Saengruksawong et al. 2012; Kongsager et al. 2013; Miao 2013; Sun 2013; Maggiotto et al. 2014; Nizami et al. 2014; Xiao et al. 2014). Note: a, b, $R^2$, SEE denotes slope, intercept, coefficient of determination and model’s standard error, respectively.

<table>
<thead>
<tr>
<th>Component</th>
<th>a</th>
<th>b</th>
<th>$R^2$</th>
<th>SEE</th>
<th>$F$-value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aboveground tree</td>
<td>2.424</td>
<td>-0.473</td>
<td>0.760</td>
<td>20.170</td>
<td>41.108</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Litter</td>
<td>0.031</td>
<td>1.780</td>
<td>0.491</td>
<td>0.465</td>
<td>12.546</td>
<td>0.004</td>
</tr>
<tr>
<td>Root</td>
<td>0.272</td>
<td>3.682</td>
<td>0.527</td>
<td>3.817</td>
<td>14.459</td>
<td>0.002</td>
</tr>
<tr>
<td>Latex</td>
<td>0.939</td>
<td>-3.946</td>
<td>0.977</td>
<td>2.130</td>
<td>553.923</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Soil</td>
<td>-0.356</td>
<td>144.178</td>
<td>0.157</td>
<td>12.194</td>
<td>2.427</td>
<td>0.143</td>
</tr>
<tr>
<td>Total excluding latex C (our study)</td>
<td>2.371</td>
<td>149.175</td>
<td>0.724</td>
<td>21.685</td>
<td>34.026</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Total excluding latex C (comprehensive)*</td>
<td>3.963</td>
<td>127.780</td>
<td>0.452</td>
<td>63.430</td>
<td>19.189</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Total including latex C (our study)</td>
<td>3.310</td>
<td>145.222</td>
<td>0.826</td>
<td>22.44</td>
<td>61.785</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>