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Carbon Cycling in Teak Plantations in Comparison with Seasonally Dry Tropical Forests in Thailand

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1. Introduction

Tropical deforestation has become a significant source of increased atmospheric CO_2 concentration, hence efforts to promote several actions for reducing emissions from deforestation and forest degradation (REDD) in the international society, one important example of which is afforestation in deforested areas (Gibbs et al., 2007). Recently, Pan et al. (2011) estimated that the global average of the gross emission rate of tropical deforestation was 2.9 petagrams of carbon (Pg C y^{-1}) from 1990 to 2007 and that tropical regrowth forests were partially compensated for by a carbon sink of 1.6 Pg C y^{-1} within an area of 557 Mha. In contrast, the carbon sink from intact forests, not substantially affected by direct human activities, was 1.19 Pg C y^{-1} within an area of 1392 Mha, suggesting that tropical plantations acted as strong carbon sinks due to rapid biomass accumulation.

Teak (*Tectona grandis*), as a tall tree species indigenous to India, Myanmar and Thailand and growing in seasonal dry tropical areas in Asia (Bunyavejchewin, 1983), is highly rated among hardwood plantations due to its durability, mellow color, and long straight cylindrical bole. Although natural teak is distributed in relation to productive soils, derived from e.g. limestone (Tanaka et al., 1998), teak is planted over many tropical countries, such as Nigeria, the Côte d'Ivoire, and Sierra Leone in Africa, and Costa Rica, Panama, Colombia, Trinidad and Tobago and Venezuela in central America, as well as Asian countries (Kashio & White, 1998; Pandey & Brown, 2000). By the year 2000, global teak plantation area reached 5.7 million hectares (FAO, 2001) and is still growing for investment by small landholders in agroforestry management as well as industrial wood supply (ITTO, 2004). However, the expansion of teak plantation has been propounding discussion from environmental perspectives, such as reduced biodiversity by mono-cultural plantations involving the clearing of undergrowth vegetation; soil erosion by fire treatment and litter raking; nutrient losses during harvesting; the spread of pests such as defoliators, the bee hole borer, skeletonizer; and the effects of water cycling (Niskanen, 1998; Pandey & Brown, 2000; Hallett et al., 2011).

Nowadays, one of the incentives for planting teak is to meet the demand in terms of carbon sequestration by indigenous tree species, at least in Indochina, with high economical return (Pibumrung et al., 2008; Jayaraman et al., 2010). However, despite several studies on carbon and biomass distribution in teak plantation in many countries, the carbon cycling of teak plantation has rarely been reported (Khanduri et al., 2008; Kraenzel et al., 2003; Viriyabuncha et al., 2002; Pande, 2005). Teak plantation production varies widely among countries and depending on soil conditions (Enters, 2000; Kaosa-ard, 1998). For example, the mean annual increment ranged from 2.0 m^3 ha^{-1} y^{-1} in poor sites in India to 17.6 m^3 ha^{-1} y^{-1} in prime sites in Indonesia with 50 year rotation periods (Pandey & Brown, 2000). Thus, the quantative illustration of carbon cycling in teak plantations is useful for understanding the key carbon sequestration channels, which may serve as the basis for improving forest management.

In this study, we estimated carbon stocks and fluxes of teak plantations in western Thailand, where productive soil was formed by underlying limestone and sandstone geological series (Suksawang et al., 1995). According to carbon allocation and carbon dynamic models (Richter et al., 1999; De Deyn et al., 2008), site productivity usually enhances carbon accumulation in soil by returning litter above and below ground to the soil. To understand the effects of forestry plantation on the carbon sequestration potential, carbon dynamics in adjacent natural forests were compared.

2. Materials and methods

2.1 Study sites, vegetation and soil

The study site was located in the Mae Klong Watershed Research Station (14˚35'N, 98˚52'E, Fig. 1), Lintin, Thong Pha Phum, Kanchanaburi Province, western Thailand (Takahashi et al., 2009). The annual mean air temperature at the station is about 25°C, ranging from 9.3 to 42.2°C, and the annual mean precipitation is 1,650 mm, most of which falls during the rainy season from April to October (Suksawang et al., 1995). Altitudes at the study sites ranged from 150 to 350 m a.s.l. In the watershed, the CO_2 and water exchange of the forest were monitored by a flux tower (Fisher et al., 2009; Saigusa et al., 2008).

Fig. 1. The location of the Mae Klong Watershed Research Station in Thailand.

Two plots were established in the teak plantation: young aged stand (T1, planted in 1992) and middle aged and gmelina (*Gmelina arborea*) mixed stand (T2, planted in 1977). The T1 plot had 530 trees ha^{-1} and its basal area at a height of 1.3 m was 6.0 m^2 ha^{-1} in 1996 (Photo 1.). In T2, the tree density and the basal area of teak were 384 trees ha^{-1} and 17.4 m^2 ha^{-1}, respectively, while those of gmelina were 181 trees ha^{-1} and 12.3 m^2 ha^{-1}, respectively, in

Photo 1. Photographs of the study sites. Top left: 3-year-old teak (T1), top right: 7-year-old teak (T1), middle left: 16-year-old teak (T2), middle right: natural forest (MDF), bottom left: bamboo undergrowth in the natural forest, and bottom right: aerial photo of the Mae Klong watershed research area (back hills).

1996. The teak plantation was mainly distributed over a lower slope area, which was formerly cultivated land e.g. for upland rice.

The adjacent natural forest was of the mixed deciduous forest (MDF) (Rundel & Boonpragob, 1995). Detailed descriptions of the vegetation were given by Marod et al. (1999). The dominant tree species were *Shorea siamensis*, *Vitex peduncularis*, *Dillenia parviflora* var. *Keruii*, and *Xylia xylocarpa* var. *Keruii*, while four bamboo species were mixed as undergrowth vegetation (Takahashi et al., 2007). The forest was spread on a hill behind the teak plantation. Despite being so-called natural forest, it is still thought to have been historically affected by human disturbances such as hunting and collecting forest products, forest fires, and logging, as the other tropical dry forest (Murphy & Lugo, 1986), as well as natural disturbances by winds and storms (Baker et al., 2005).

Soil with a relatively high pH and rich in exchangeable calcium is classified as Alfisols (Soil Survey Staff, 2010) and derived from sedimentary rock, gneiss and limestone. Concisely, the soil pH (H_2O) is 5.7 - 7.1; exchangeable cations (cmol kg^{-1}) are 5.8 - 17.9 for Ca, 1.4 - 3.0 for Mg and 0.5 - 1.3 for K respectively; the cation exchangeable capacity is 10.3 - 16.2 cmol kg^{-1} and the base saturation is 75 – 127%. Soil texture is classified into sandy loam, loam, or clay loam and the soil is well drained. The chemical and physical properties of the soil in the study sites were also reported elsewhere (Takahashi et al., 2009, 2011).

2.2 Tree enumeration, litterfall, and fine root mass

Plots for tree enumeration were 40 × 60 m for T1 and 30 × 60 m for T2 in the teak plantation. In the watershed, plantation trees were planted at a spacing of 4 × 4 m. For the natural forest, enumeration was performed within an area 200 × 200 m on the slope (Marod et al., 1999). Diameter at the breast height (DBH, 1.3 m above the ground) was measured every year in the plantation and every two years in the natural forest.

The litterfall was measured using 10 litter traps with 1 × 1 m openings in the teak-gmelina plantation (T2), but not in the young teak plantation (T1). For the natural forest, 100 traps were installed in grids at 20 m intervals. Litter was collected once or twice a month and the oven dry mass was weighed (70 °C). The conversion factor to carbon mass used was 0.47.

Fine and small root biomass (< 2 cm in diameter) was measured by a soil column with an area 15 × 15 cm and a depth of 15 or 30 cm. The sampling was performed in triplicate in November 1998, the beginning of the dry season. Dead roots were eliminated and bamboo roots were separated by visible inspection. Root diameters (mm) were classified into <1, 1 – 3, 3 – 5, 5 – 10, and 10 – 20 and the oven dry weight was determined. The carbon concentration was assumed to be 0.45 gC g^{-1}.

2.3 Carbon stocks in ecosystem compartments

To calculate the carbon stock in living biomass, biomass conversion equations from basal areas (Kiyono et al., 2010) were used for estimating carbon in leaves, branches, stems, and roots. The wood density of tree species, carbon contents of leaves and woody materials were all collected from the IPCC report (IPCC, 2006).

Soil carbon stocks were determined at the representative soil profile in the plots. For the natural forest, soil pits were set on a slope at different topographical positions: ridge, upper and lower slope positions and a soil sample was taken from each soil horizon described in the soil survey. The soil carbon concentration was analyzed using the dry combustion method (NC analyzer, Shimadzu Co., Kyoto, Japan), while the soil bulk density was measured using a 4 × 100 cm² cylinder core. The soil carbon stock was calculated by multiplying the carbon concentration by the soil bulk density of the soil layer and cumulating to a certain depth. The litter (forest floor) was collected using a 0.5 × 0.5 m frame with four replications.

2.4 Soil respiration rate

The soil respiration rate was measured using the closed chamber method (Takahashi et al., 2009). The steel chamber used was 30 cm in both diameter and height. About 20 min after the cover had been sealed, the CO_2 concentration in the chamber headspace was determined by an infrared gas analyzer (ZFP5, Fuji Electronics Co., Ltd., Japan), while the soil respiration rate was calculated using a linear model of increasing CO_2 concentration with temperature correction. In this measurement, we manipulated trenching around the chamber and litter removal to separate the respiration sources of the roots, organic layer, and soil. Detailed results were reported elsewhere (Takahashi et al., 2009, 2011).

3. Results and discussion

3.1 Stock and growth of trees

In the teak plantation, plots T1 and T2 showed constant accumulation of carbon in the biomass. The teak biomass was 3.8 MgC ha^{-1} at 3 years, increasing to 28.6 MgC ha^{-1} at 6 years in T1 (Fig. 2). Biomass in T2, where one third of the planted trees were gmelina, was 56 MgC ha^{-1} for teak, 37.5 MgC ha^{-1} for 15-year-old gmelina, increasing to 86.9 MgC ha^{-1} for teak and 59.8 MgC ha^{-1} for gmelina at 20 years. Although plot T2 was a mixed stand and the stand age differed from plot T1, the T1 and T2 growth rates were comparable. Combining these stands, the growth rate of these plantations was estimated as 9.3 MgC ha^{-1} y^{-1} by linear regression ($r = 0.999$, $p < 0.01$). Total biomass consisted of 1.9% for leaves, 14.8% for branches, 69.2% for stems and 14.1% for roots aged 20 years at plot T2.

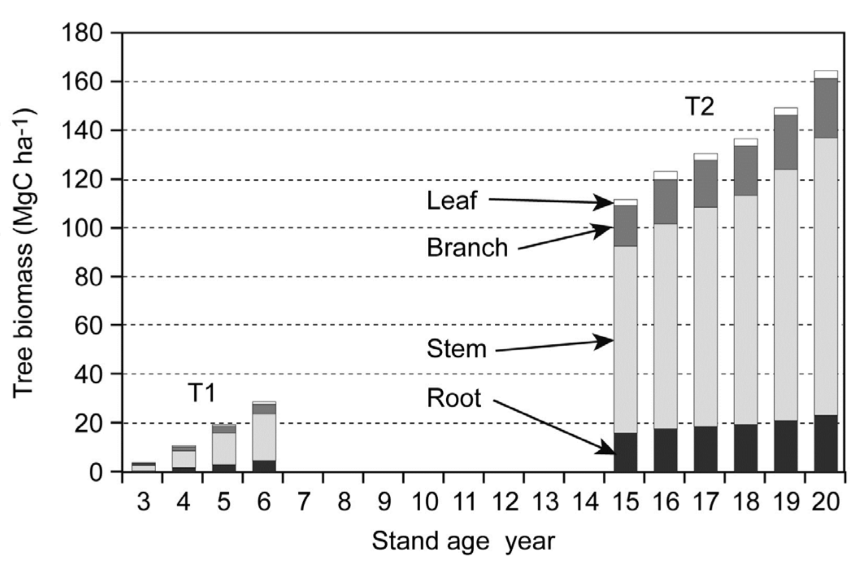

Fig. 2. Leaf, branch, stem and root biomass in teak plantations. Plots T1 and T2 are shown in the same figure according to the stand age.

Previous reports on carbon stocks in teak plantations in several countries were summarized in Table 1. Among the reference data, the site productivity of the teak in this watershed was the highest value. The increase rate of carbon stock of 9.3 MgC ha^{-1} y^{-1} was almost equivalent to 24 m^3 ha^{-1} y^{-1} for the stem volume increment, which would almost represent the upper limit of the mean annual increment of teak plantations under short rotation (< 20 years) system (Enters, 2000; Kiyono et al., 2007). This is probably due to the soil properties: well drained, rich in calcium, and high soil pH (Takahashi et al., 2009), namely ideal soil conditions for teak growth (Kaosa-ard, 1998; Tanaka et al., 1998).

Country, region	AG†	BG‡	Litter	Soil§	Stand age	Tree density	Soil pH	Ref.¶
		(MgC ha^{-1})			(y)	(ha^{-1})		
Panama, Boquerón	91.8	13.8	3.6	225 (200cm)	20	586	6.6	1)
Panama, Peňas Blancas	122.2	18.4	3.3		20	566	6.2	
Panama, Tranquilla	117.1	17.6	3.2		20	621	5.9	
Panama, Agua Claras	86.8	13.1	3.5		20	723	6.1	
Nigeria, Oyo	21.2		0.8		5	1184		2)
	57.2		2.2		8	1088		
	57.0		1.4		11	1100		
	67.1		1.5		14	988		
India, Chhindwara	17.8	4.9			16	2500	7.9	3)
India, Kerala	78.7				20	217	5.03	4)
	92.2				20	250	5.36	
	96.0				20	300	5.74	
	70.9				15	233	5.05	
	56.1				15	217	5.36	
	82.5				15	333	5.81	
Thailand, Prachuap Khiri Khan	43.7	13.8		56.77 (50cm)	15			5)
Thailand, Lampang	35.6	9.1		221 (50 cm)	17	844		6)
	41.2	8.2		137 (50 cm)	22	544		
Thailand, Kanchanaburi	24.1	4.4		108 (100cm)	6	530	7.1	7)
	141.0	23.2	2.5	123 (100cm)	20	565	6.2	

†: Aboveground biomass, ‡: Belowground biomass, §: cumulative soil depth in parentheses,
¶:Reference 1) Kraenzel et al., 2003; 2) Mbaekwe & Mackenzie, 2008; 3) Pande, 2005; 4) Chandrashekara, 1996; 5) Meunpong et al., 2010; 6) Hiratsuka et al., 2005; 7) This study.
Note: Dry mass was converted to carbon mass by a factor of 0.5.

Table 1. Comparison of carbon stocks in teak plantations in the seasonally dry tropics.

In the natural forest, the density of trees above 5 cm in DHB was almost stable with slight fluctuation during the 8 years of monitoring, ranging from 174 to 199 trees ha^{-1} and 16.9 to 17.7 m^2 ha^{-1} for basal areas (Fig. 3). However, the tree density was rather low, compared to the forest in Huai Kha Khaeng, about 120 km north of Mae Klong, where 438 trees (> 10 cm in DBH) ha^{-1} (Bunyavejchewin et al., 2001), suggesting a history of high disturbance in this area (Baker et al., 2005). Total tree biomass in 2000 was 139 MgC ha^{-1}, consisting of 1.5 MgC ha^{-1} for leaves, 19.3 MgC ha^{-1} for branches, 101 MgC ha^{-1} for stems, and 17.8 MgC ha^{-1} for roots. Because carbon densities in the Thai forests vary with forest type (Ogawa et al., 1961, 1965), our comparison was limited to the aboveground biomass of trees of the MDF (mixed deciduous forest) type. Similarly, low carbon densities were reported such as 48.14 MgC ha^{-1} in Pong Phu Ron station (Terakunpisut et al., 2007) and 24.79 and 50.58 MgC ha^{-1} for secondary and primary MDF in Phetchabun province (Kaewkron et al. 2011). As for MDF comparable forests from the early ecological study in Thailand, Ogawa et al. (1965) showed an aboveground dry mass of 157 Mg ha^{-1} (77 MgC ha^{-1}) for a forest classified as monsoon forest-savanna ecotone in Chiang Mai province and that of 103 Mg ha^{-1} (51 MgC ha^{-1}) for a mixed savanna forest in Tak province. Although carbon accumulation in MDF varies widely, our result seems typical of this forest type.

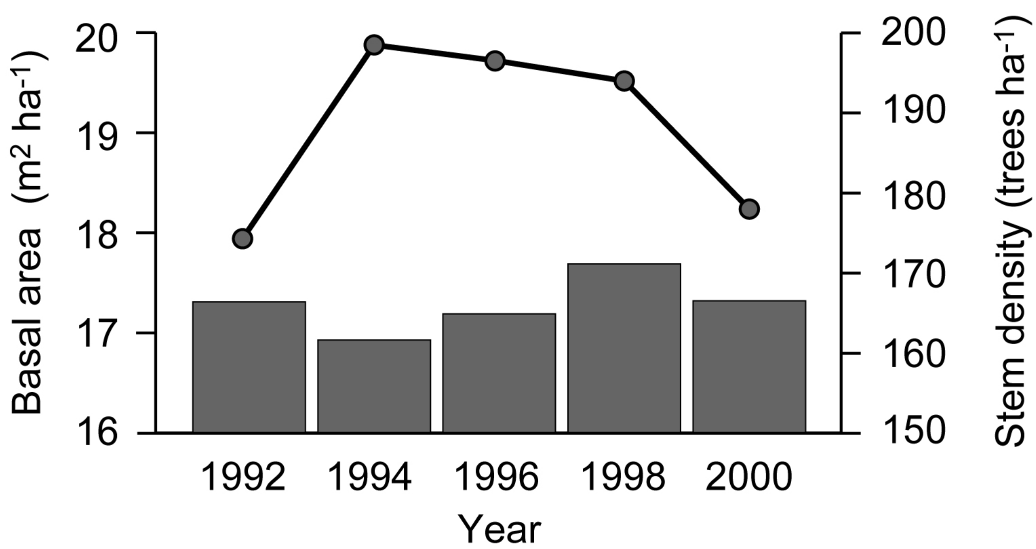

Fig. 3. Changes in stem density (DBH > 5 cm, dots and lines) and basal area (bars) in the natural forest.

Despite the low tree density, no apparent increment of carbon accumulation was detected in the natural forest studied. The natural forest nearby the teak plantation seemed static or in balance with the sequestration of carbon in the forest biomass. Our observation confirmed that most individual trees had increased steadily but some were dead with broken stems and standing dead, probably due to competition during the 8-year monitoring period (Marod et al., 1999 and unpublished data by Marod). In terms of the recruitment of trees, forest fires and drought stress would control the survival rates of tree seedlings and seed germination as well (Marod et al., 2002). In addition, shading by bamboo leaves during the rainy season influences the survival rate of seedlings (Marod et al., 2004). Similar findings showing that abundance in terms of seedlings and species had declined under bamboo in the MDF were reported in the Loei province of Thailand (Larpkern et al., 2011).

3.2 Litterfall

Annual litterfall in the teak-gmelina stand (T2) was 2.22 Mg ha^{-1} y^{-1} on average, consisting of 89.3% for leaf, 2.5% for fruit, and 8.2% for others such as bark. Of the leaf litter, 52.8% was counted for teak, 29.0% for gmelina, and 18.2% for other leaves (Fig. 4). The litterfall in the natural forest was 2.38 Mg ha^{-1} y^{-1}, on average, consisting of 61.5% leaves, 2.3% flowers, 7.7% fruit and 28.5% for others such as branches and bark (Fig. 5). About half the leaf litter (51.7%) was bamboo leaves. The litterfall tended to peak during January to March in both the natural forest and teak plantation: during this quarter, 46% of the litterfall fell in the natural forest and 56% in the teak plantation.

Seasonal patterns of litterfall were reported in several seasonal tropical forests with seasonal drought (e.g. Martínez-Yrízar & Sarukhán, 1990; Bunyavejchewin, 1997), usually as a dry matter basis. For teak plantations, 9.0 Mg ha^{-1} of annual litterfall, 90% of which was leaf litter and 70% or so of which fell during the dry season in Nigeria (Egunjobi, 1974). In India, total litterfall in teak plantations ranged from 3.3 to 4.5 Mg ha^{-1} (Pande et al., 2002). In the natural forests of Thailand, levels of 6.8 Mg ha^{-1} in *Shorea henryana* and 6.4 Mg ha^{-1} in a *Hopea ferrea* were observed (Bunyavejchewin, 1997). Mixed deciduous forest with teak showed total litterfall of 7.98 Mg ha^{-1} (Thaiutsa et al., 1978). The annual litterfall and proportion of the same in this study were comparable to previous studies of seasonal dry tropical forests (Martínez-Yrízar, 1995).

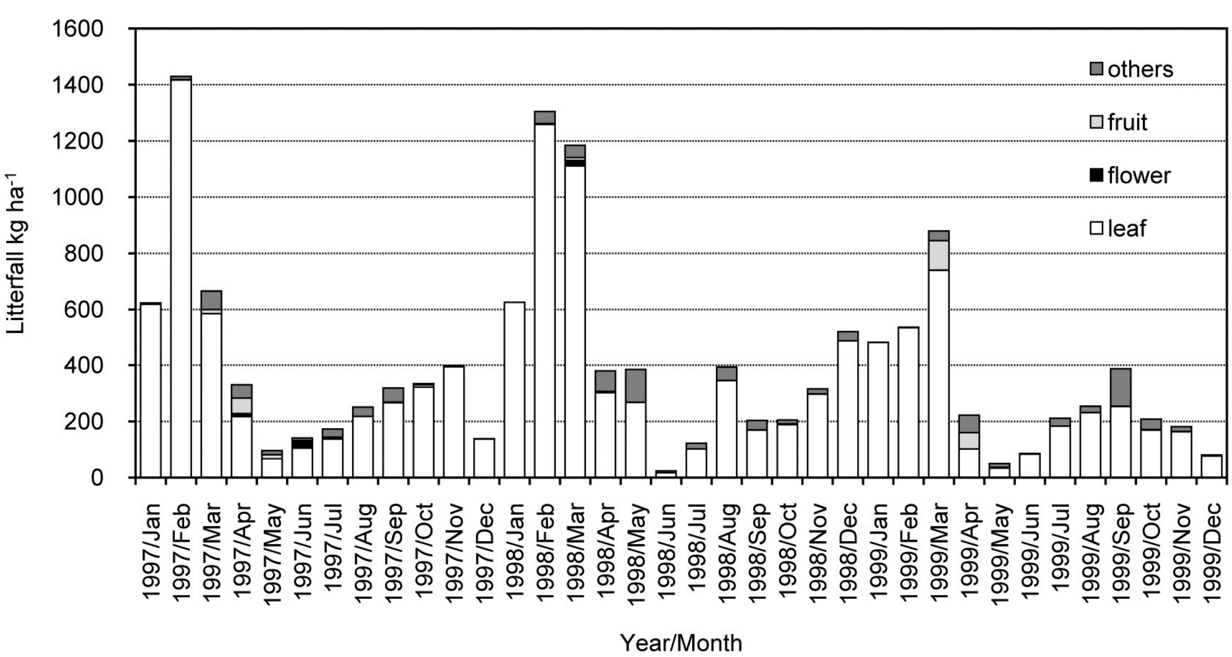

Fig. 4. Dry weight of monthly litterfall in the teak-gmelina plantation (plot T2).

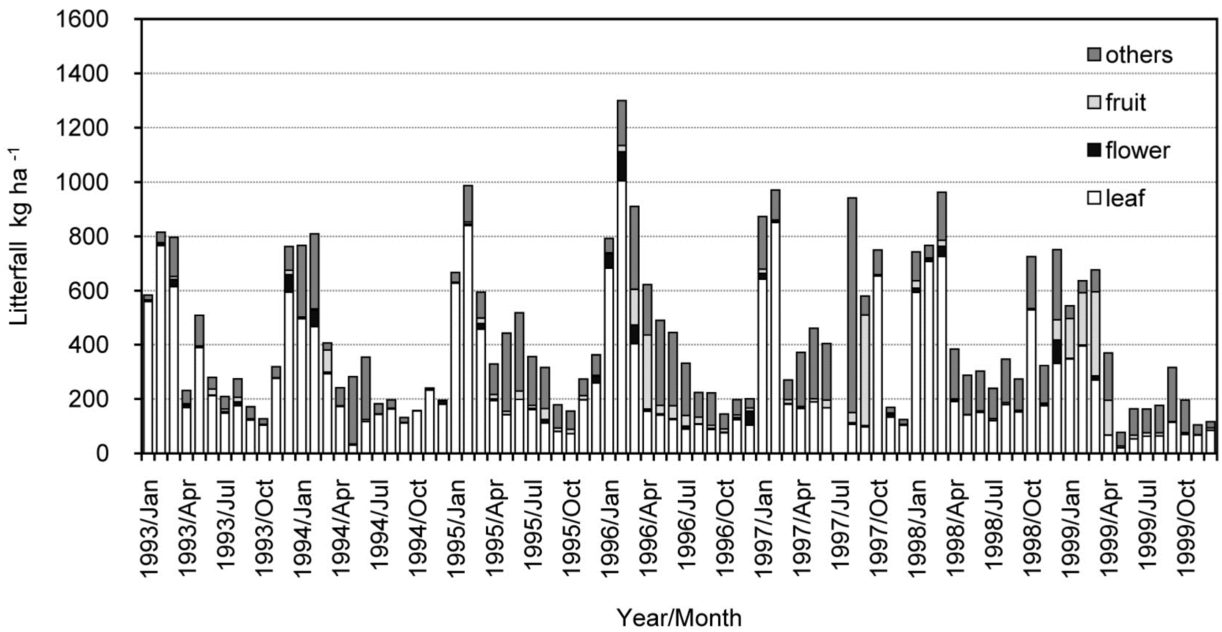

Fig. 5. Dry weight of monthly litterfall in the natural forest.

3.3 Root distribution and biomass

Fine root biomass (< 1 and 1 - 3 mm) was concentrated in the surface soil layer (0 - 15 cm) in all the plots studied (Fig. 6). The teak plantation had a sparse rooting system: fine roots (< 3 mm) with density in the 0 - 15 cm soil layer of 392 and 219 g m^{-3} for T2 and T1 respectively, compared to those in the natural forest (1144 g m^{-3} on average). In the 0 – 30 cm soil layer, fine root biomass (< 3 mm) was 0.47 and 0.32 MgC ha^{-1} for T2 and T1. Total fine and small root biomass (< 2 cm) at depths of 30 cm and 1 m was 2.3 and 2.7 MgC ha^{-1}, respectively, for plot T2 and 0.4 and 1.6 MgC ha^{-1} for plot T1. In the natural forest, the bamboo roots were mostly fine roots (< 3mm) at the surface (725 g m^{-3}), while the fine root biomass (<3 mm) of the 0 – 30 cm layer was 2.8 MgC ha^{-1} on average. Total root biomass (< 2 cm) was 4.0 MgC ha^{-1} at a depth of 30 cm and 8.8 MgC ha^{-1} at a depth of 1 m. These data are included in the root biomass estimated by the allometric equations above.

Although limited data is available for root biomass estimation in seasonal tropical forests, previous research revealed that fine root growth and density in seasonal tropical forests were highly controlled by soil hydrological regime (Cuevas, 1995). Our root biomass measurement, conducted at the beginning of the dry season, was probably lower than that in the rainy season. According to the review data by Cuevas (1995), the root mass in the wet season was about 1.5 times larger than that in the dry season. Singh & Srivastava (1985) found that the dynamics of root tip development, indicating growth and activity of fine roots, occurred mostly in the top 20 cm soil layer in teak plantations and that the highest root tips were observed in the mid rainy season. Similar fluctuations were found in both natural and Mexican dry forests (Kummerow et al., 1990; Kavanagh & Kellman, 1992). We could not clarify the fine root dynamics from the one-time measurement. However, the relative proportion of root biomass between the teak plantation and natural forest would be reasonable because the differences in root respiration as a proportion of total soil respiration between the teak plantation (15%) and the natural forest (19.4 – 33.6%) were comparable to the difference in root biomass of the same (Takahashi et al., 2011). These findings suggest that carbon flux by root necromass and exudates from fine root to mineral soil may be higher in natural forest than teak plantations, although high carbon accumulation by a developing living root system occurred at a rate of 1.3 MgC ha^{-1} y^{-1}; as calculated by total biomass increment and the root biomass proportion of these forests.

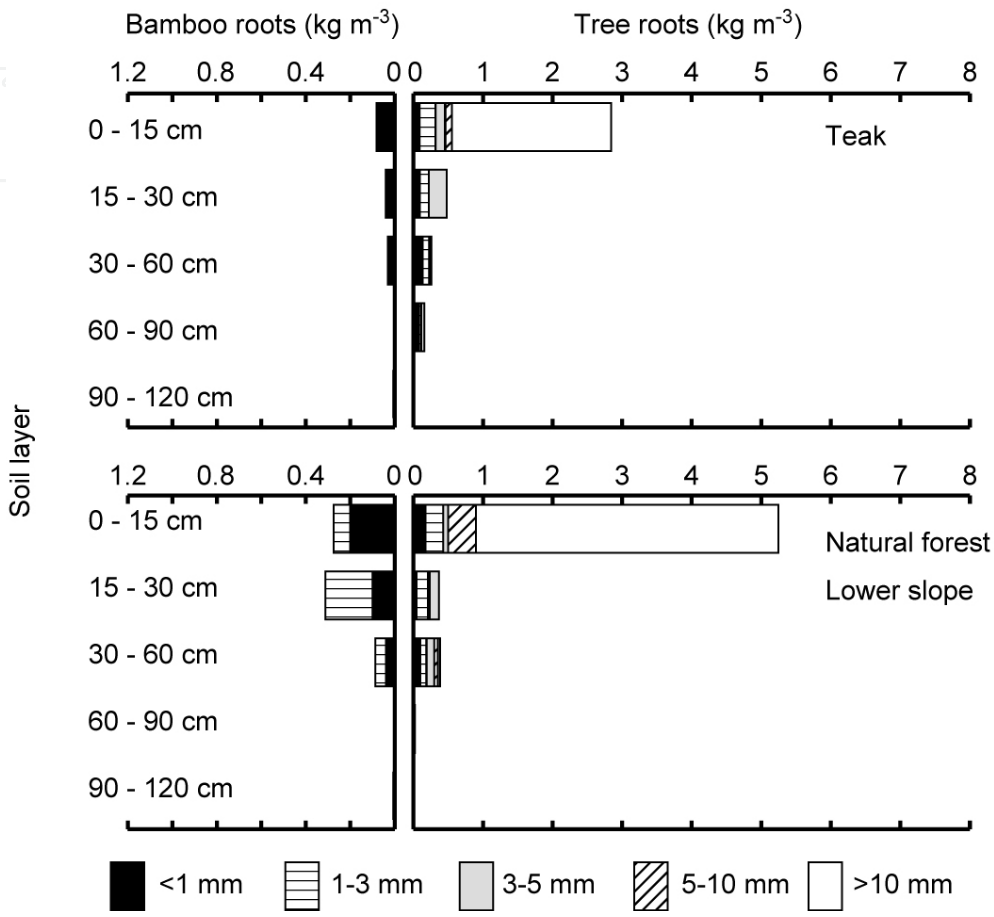

Fig. 6. Vertical distribution of fine and small roots density (< 20 mm) in the teak plantation (T1) and the natural forest (lower slope position). Bamboo roots are shown in the left-hand side and tree and other roots are in the right-hand side.

3.4 Soil carbon stock

In the teak plantation, soil carbon stocks at a depth of 1 m were 108 and 124 MgC ha^{-1} for plots T1 and T2 respectively (Fig. 7). The surface layer 0 – 15 cm had 34 MgC ha^{-1} in both plots T1 and T2. In the natural forest, carbon stocks in soil at a depth of 1 m varied with slope position and tended to have a larger ascribing slope, ranging from 113 to 178 MgC ha^{-1} (Takahashi et al., 2011, and unpublished data by Takahashi). The soil carbon stock in the soil layer of 0 - 15 cm was 32 and 38 MgC ha^{-1} in the lower and middle slope positions respectively.

Tangsinmankong et al. (2007) reported that soil carbon stocks up to 1 m depth under teak plantations of varying age ranged from 78.8 to 157 MgC ha^{-1} and that those in the 0 – 15 cm layer had 26.7 to 37.2 MgC ha^{-1} in the same district of this study. In peninsular Thailand, soil carbon in the 0 – 50 cm layer was 56.8 MgC ha^{-1} in a 15 year-old teak plantation with tree biomass of 57.5 MgC ha^{-1} (Meunpong et al., 2010). Soil carbon in the 0 – 50 cm soil layer under a teak plantation in Colombia was 54.9 MgC ha^{-1} (Usuga et al., 2010). These values are comparable to our results. In north Thailand, however, Hiratsuka et al. (2005) reported very high carbon stock in soils in 0 – 50 cm layers, 211 MgC ha^{-1} in 17 year-old stand, with 2 × 4 m spacing, by accumulating high organic carbon in the top soil layer, and 137 MgC ha^{-1} in the 22 year-old stand with 4 × 4 m spacing. In Panama, 225 MgC ha^{-1} was stocked up to the bottom of the soil profile, almost 2 m in depth, under 20 year-old teak plantation (Kraenzel et al., 2003). In MDF of Thailand, the soil carbon stocks at depths of 15 cm and 1 m were 26.7 and 71.0 MgC ha^{-1} (Tangsinmankong et al., 2007). Soil carbon at a depth of 0 – 30 cm (MgC ha^{-1}) on the sandstone and conglomerate was 27.6 while that on the limestone was 74.9 under MDF in Thailand (summarized by Toriyama et al., 2011).

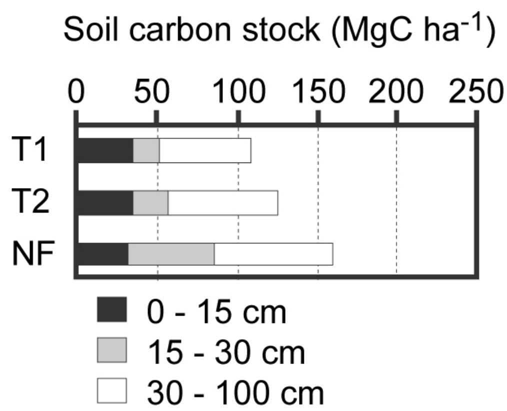

Fig. 7. Vertical distributions of soil carbon stocks in the teak plantations (plots T1 and T2) and natural forest (NF).

It is difficult to compare the results of soil carbon stock between different cumulating depths and different soil groups, which are not identified in some reports. Usuga et al. (2010) pointed out the importance of land-use history for analyzing soil carbon stocks, while Sakai et al. (2010) reported that the accumulation of carbon stock after conversion from arable land to forest plantation was only evident in the organic layer and the surface soil layer with 0 – 5 cm in the Japanese cedar and cypress stands younger than 25 years-old.. With reference to fine root distribution in the top 0 – 15 cm soil layer and litter on the forest floor, comparison of soil carbon stocks should be limited to the upper soil horizons, where the active component of soil organic carbon is concentrated. In addition, Toriyama et al. (2011) showed the importance of parent materials for soil carbon accumulation: basaltic and calcareous parent materials accumulated about twice the carbon stock compared to sedimentary rocks in the forest ecosystems in Cambodia and Thailand. The top soil carbon accumulation, ranging from 32 to 38 MgC ha^{-1} within the 0 – 15 cm layer, was relatively high, probably due to the influence of the limestone parent material, although no clear differences emerged between the teak plantation and the natural forest.

3.5 Soil respiration

The soil respiration rate (gC m^{-2} d^{-1}) showed seasonal fluctuation, peaking in the rainy season and declining in the dry season; ranging from 1.44 to 5.27 for plot T1, 1.71 to 5.46 for plot T2, and 1.85 to 7.21 for plots on the natural forest slope respectively. Applying equations fitting the relationship between soil moisture in the 0 – 30 cm layer monitored by TDR sensors and soil respiration rates, annual carbon efflux from the forest floor was estimated (Takahashi et al., 2009, 2011). Annual carbon efflux in plots T1 and T2 were 11.5 and 10.6 MgC ha^{-1} y^{-1}, respectively. In the natural forest, the soil respiration rate varied with the slope position on the hill (Takahashi et al., 2011) hence the average of the lower and upper slopes was used in this study for annual carbon efflux. In the natural forest, the carbon efflux was 17.7 MgC ha^{-1} y^{-1} on average. To distinguish the CO_2 sources, trenching to separate root respiration and litter removal in the chamber were manipulated (Takahashi et al., 2009, 2011). The proportions of roots, litter, and soil respiration were 15, 17, and 68%, respectively, for plot T2, and 27, 23, and 50 %, respectively, for the natural forest, on average.

Soil respiration is a key channel for returning photosynthesized carbon into the atmosphere, which has been intensively studied in forest ecosystems (e.g. Davidson et al., 2000). In general, annual soil carbon efflux correlates with annual rainfall and the mean annual temperature, as well as with annual litterfall (Raich & Schlesinger, 1992; Raich & Tufekciogul, 2000). For the soil respiration rate, Adachi et al. (2009) reported an average of 6.82 ± 3.55 gC m^{-2} d^{-1} during the rainy season and 2.63 ± 1.35 gC m^{-2} d^{-1} in a forest in Huai Kha Khaeng in northern Thailand. In a dry dipterocarp forest (DDF) in Ratchaburi, western Thailand, the soil respiration rate ranged from 1.26 gC m^{-2} d^{-1} in the dry season to 3.93 gC m^{-2} d^{-1} in the rainy season (Hanpattanakit et al., 2009). Annual carbon efflux from the forest floor was estimated at 13.4 MgC ha^{-1} y^{-1} under a dry evergreen forest (DEF), 12.1 MgC ha^{-1} y^{-1} under an MDF, 10.7 MgC ha^{-1} y^{-1} under a DDF in the Mae Klong watershed basin (Panuthai et al., 2006), and 25.6 MgC ha^{-1} y^{-1} under a hill evergreen forest (HEF) in Chiang Mai, northern Thailand (Hashimoto et al., 2004). As for teak plantations, the soil respiration rate has rarely been measured. In Khon Kaen Province, northeastern Thailand, 15.0 MgC ha^{-1} y^{-1} of CO_2 efflux in a teak plantation on sandy soil was reported (Funakawa et al., 2007). These data, including our results, suggest that soil respiration rates in teak plantations are likely to be similar to those for natural forest vegetation.

3.6 Carbon cycling in teak plantations

The carbon balance in plot T2 of the teak-gmelina plantation was depicted in Fig. 8. To draw this picture, we assumed comparable growth rates for the T1 and T2 plantations, despite the fact T2 were mixed forest with gmelina. We did not measure the litter decomposition of teak and gmelina leaves but, according to the partitioning of soil respiration sources, annual litterfall would be decomposed within a year, which is in accordance with our field observation that leaf litter on the forest floor disappeared during the rainy season. In this watershed, leaves of *Shorea siamensis* and bamboo swiftly decayed; 95 and 85 % of the initial weight having decomposed within a year (Somrithipol, 1997). A rapid decomposition rate was also often reported for teak leaves, usually more than 90 % in a year in several countries (e.g. Sankaran, 1993; Maharudrappa et al., 2000; Pande, 2005). As for forest floor vegetation, this was not measured because in T1, upland rice was initially cultivated between planted teaks for the first two years, whereupon weeding was performed each year. In T2, understory vegetation was sparse, due to bamboo flowering and dying two to three years before our observation commenced. Bamboo recovery was slow compared with the open area outside the forest, hence we ignored forest floor biomass in the teak plantation in this study.

Under these assumptions, the net primary production (NPP), as the gross rate of biomass production (GPP) minus the respiration cost (R): NPP = GPP – R, can be calculated and expressed as an increment of biomass plus necromass, such as litterfall and root litter, while some is consumed by herbivores. In the teak-gmelina plantation, NPP was estimated to be at least 11.5 (=9.3+2.2) MgC ha^{-1} y^{-1}, excluding underground processes. This value would be reasonable and relatively high for plantations in the tropics, referring to the review paper by Pregitzer & Euskirchen (2004). As comparable data, Imvitthaya et al. (2011) estimated the NPP in teak plantations in northern Thailand using BIOME-BGC Model and Spot data and with estimation ranging from 6.06 to 7.76 MgC ha^{-1} y^{-1} with yearly variation.

As for the natural forest, no apparent tree growth was observed from the tree census. If the carbon is balanced, NPP was equivalent to at least over litterfall. Clark et al. (2001) evaluated NPP in tropical primary forests, which ranged from 1.7 to 11.8 MgC ha^{-1} y^{-1} for the lower boundary based on conservative estimates, and featuring close correlation with aboveground biomass increment and fine litterfall. Our data showing the slow carbon sequestration rate by trees seems reasonable. Compared to the carbon cycling in the natural forest, we conclude that teak plantations are certainly valuable for sequestrating carbon, especially the portions above ground, in this area where the soil conditions favor teak.

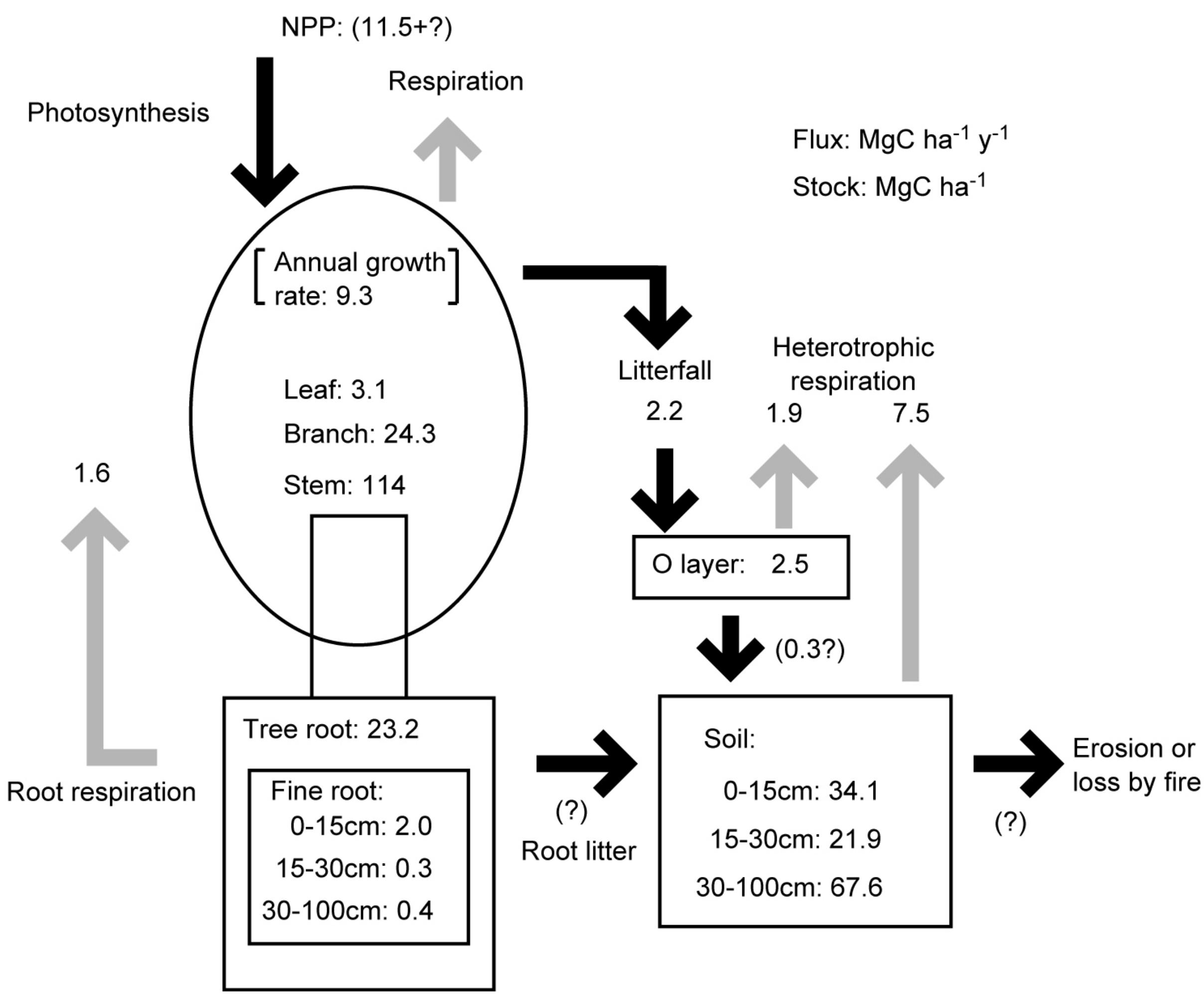

Fig. 8. Carbon cycling of the teak-gmelina plantation (T2). Figures in parentheses indicate uncertain estimates.

3.7 For sustainable teak plantation management

Soil carbon stock usually increased over time after planting trees (Sakai et al., 2010), due to carbon input from litterfall and the turnover of dead roots (Richter et al., 1999), meaning the higher growth of forest plantation would lead to higher soil carbon accumulation. However, despite high production in the plantation studied, there was no apparent difference in the soil carbon between T1 and T2. We speculate that surface soil erosion spoiled the soil carbon sequestrated under the plantation. During our observation, we found that surface soil was eroded due to raindrop splashes in the rainy season, especially in plot T2, which seemed to prevent soil carbon accumulation in the top soil layer. Poor understory vegetation, which induced bamboo flowering and death, dark conditions under the teak canopy, and quick litter decomposition seemed to create soil conditions leading to a bare and exposed surface. A similar observation of erosion under teak plantations was reported by Ogawa et al. (1961), Tangtham (1992), and Boley et al. (2009). This risk of soil erosion in teak plantations, caused by large raindrops falling from broad and large teak leaves, has been pointed by Hall & Calder (1993) and Calder (2002). Another possible risk of preventing carbon accumulation in the soil would be forest fires. Although teak resists fire, litter on the forest floor is lost if fires occur in the dry season, which is considered to be the main cause of low soil carbon accumulation in Myanmar teak plantations (Suzuki et al., 2007).

As well as surface soil, subsurface soil also showed no carbon accumulation in the teak plantation: Soil carbon stocks in the subsurface layer (15 – 30 cm) were smaller than those in the natural forest (Fig. 7). Similarly, in Panama, Kraenzel et al. (2003) also observed that teak plantations on abandoned land promoted no significant increases in soil carbon storage, despite considerable biomass growth. After harvesting, tree stumps remained and decomposed, which may have contributed to the belowground carbon stock to some extent in the short-term. However, for long-term soil carbon storage, undergrowth vegetation with deep rooting systems may help accumulate carbon stock in the subsurface layer.

Apart from soil management, the carbon cycling scheme in Fig. 8 suggests that teak plantations in this watershed are likely to be harvestable with a short rotation cycle, e.g. 20 – 30 years. Such short rotation is also beneficial in terms of carbon sequestration, while the parent material, limestone, of this watershed would promise high future productivity of the soil. However, ideal sites for teak plantation now face competition with agricultural crops and teak is often planted in sites with poor fertility (Enters, 2000), which would thus require longer rotation periods. Appropriate management should be selected in accordance with the site characteristics and management intensity. For sustainable forest management, there is still scope to improve teak plantations from several perspectives, e.g. biodiversity, carbon sequestration, and wood quality (Nair & Souvannavong, 2000).

General criticisms of monoculture plantations in terms of reducing biodiversity were periodically reviewed (e.g. Hartley, 2002; Brocherhoff et al. 2008), with poor undergrowth vegetation in young teak plantations with narrow spacing an example of a serious case. To improve monoculture plantations, mixture with other species, gmelina in our case, would be a live option, although silvicultural prescriptions must be developed. The landscape design of plantations and corridor arrangements may also be helpful (Fischer et al., 2006; Brocherhoff et al., 2008).

Lastly, because teak takes up high levels of nutrients and returns them to the surface soil, the aggrading effect of soil fertility was found on degraded land in Costa Rica (Boley et al., 2009). Similarly, calcium enrichment under teak plantations was observed in Myanmar (Suzuki et al., 2005). If suitable management for top soil conservation is applied, e.g. spacing, weed management, fire control, and mixed planting, teak is likely to represent promising species for land rehabilitation.

4. Conclusion

Teak has been a popular tree species for timber production in commercial and private farmland and remains a promising species for carbon sequestration in the seasonally dry tropics. A carbon cycling scheme obtained in teak (-gmelina) plantations showed a high rate of carbon accumulation in the soil of Alfisols in western Thailand which has high calcium content and high soil pH. In adjacent natural forest, no apparent carbon accumulation was observed, due to slow tree recruitment and disturbance in trees. Based on a comparison of carbon cycling in the natural forest, a teak plantation would represent a reasonable recommendation for tree species when managing plantations with carbon sequestration and high quality timber. However, no soil carbon accumulation is expected, probably due to surface soil erosion caused by raindrop splashes in poor understory vegetation and the ignition of litter by forest fire. Soil erosion control is essential under a teak canopy, which may promote additional carbon sequestration in the soil. Although the results of this study were derived from high productivity sites, teak can be planted as a rehabilitation species on degraded land as well. However, silvicultural prescription must be developed in accordance with economic benefit and ecological services side by side. To achieve this, quantitative measurement of carbon stocks and fluxes are useful for judging forest management appropriately.

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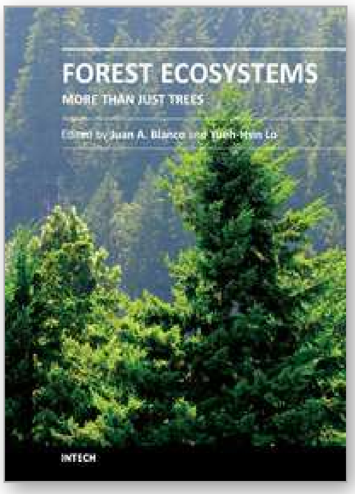

Forest Ecosystems - More than Just Trees

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The common idea for many people is that forests are just a collection of trees. However, they are much more than that. They are a complex, functional system of interacting and often interdependent biological, physical, and chemical components, the biological part of which has evolved to perpetuate itself. This complexity produces combinations of climate, soils, trees and plant species unique to each site, resulting in hundreds of different forest types around the world. Logically, trees are an important component for the research in forest ecosystems, but the wide variety of other life forms and abiotic components in most forests means that other elements, such as wildlife or soil nutrients, should also be the focal point in ecological studies and management plans to be carried out in forest ecosystems. In this book, the readers can find the latest research related to forest ecosystems but with a different twist. The research described here is not just on trees and is focused on the other components, structures and functions that are usually overshadowed by the focus on trees, but are equally important to maintain the diversity, function and services provided by forests. The first section of this book explores the structure and biodiversity of forest ecosystems, whereas the second section reviews the research done on ecosystem structure and functioning. The third and last section explores the issues related to forest management as an ecosystem-level activity, all of them from the perspective of the �other� parts of a forest.

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