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The impact of forest fires on the long-term sustainability of taungya teak reforestation in Bago Yoma, Myanmar

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ABSTRACT Taungya teak reforestation in Myanmar has a long history and is considered an exceptionally successful example of tropical plantations. However, after one cycle of taungya teak reforestation, soil quality would deteriorate as large volumes of biomass are removed from the forest ecosystem through the harvesting of teak. Therefore, the recovery of soil productivity during the period of teak growth is crucial to the successive rotation of the system. In this study, the dynamics of soil organic matter (SOM) and litter were investigated during the teak growth period to evaluate the long-term sustainability of taungya teak reforestation from the viewpoint of SOM conservation. Especially, the effect of forest fires on SOM dynamics and litter was investigated. In Kabaung Reserved Forest and Bondaung Reserved Forest, where teak reforestation has been practiced since 1884, surface soil samples were collected from teak plantations of different ages (0-96 years) for total carbon and nitrogen content analyses. In mature teak plantations, litter production and decomposition rates of leaf litter were also measured. Accretion of SOM was not observed in any of the teak plantations, even 96 years after reforestation. This absence of SOM accretion was attributed to the combustion of forest floor litter - a main source of SOM - by forest fires. Given that the occurrence of forest fires overlapped the defoliation period of teak, most of the teak litter that had accumulated on the forest floor was easily burnt. The strong positive correlation between total carbon content and the C/N ratio of surface soil in teak plantations suggested that the effect of forest fires on the long-term dynamics of soil carbon was marked. We conclude that forest fires have a detrimental effect on the long-term sustainability of taungya teak reforestation.

Key words: teak plantation, taungya, soil organic matter (SOM), litter, forest fire, long-term sustainability

INTRODUCTION

In the Bago Yoma region of Myanmar, "taungya" plantations have been successfully established for more than one century, and is considered an exceptionally successful example of tropical plantations. Taungya is a reforestation system that combines agricultural crops with forest trees (Gajaseni, 1992). In this system, the farmers who plant trees such as teak (*Tectona grandis* Linn.) are allowed to cultivate intercrops for the first few years after the establishment of a new plantation as an incentive to participate in the system.

Taungya for reforestation purposes is an adaptation of traditional shifting cultivation (Takeda, 1992) and these two systems resemble each other, as depicted in Figure 1. However, in the taungya system, a large volume of biomass is removed from the forest ecosystem through the harvesting of timber at the end of each rotation, whereas in shifting cultivation, aboveground biomass is returned to the soil for the next cultivation through the process of slash-and-burn. The export of this biomass through the harvesting of timber disrupts the nutrient cycle and subsequently diminishes soil nutrients (Fölster & Khanna, 1997; Aweto, 2001). Given that such nutrient loss may far exceed rates of replenishment by the weathering of minerals or precipitation (Fölster & Khanna, 1997), soil deterioration would occur after successive rotation under the taungya system. This potential future decrease in productivity is often called "second rotation problem" (Hase & Fölster, 1983; Bruijnzeel, 1992). While this problem is common to all plantations dedicated to wood production, decreased productivity in taungya systems is potentially more problematic as it can harm, not only the growth of trees, but also the yields of the intercrops that are the incentive for farmers to become involved in the system.

However, despite the fact that the taungya teak reforestation has been practiced in Myanmar since the mid-19th century, this second rotation problem has not yet been observed. This is thought to be mainly due to the following reason: Before the mid-1970s, the area dedicated to teak plantations in Myanmar was around 1,000 ha/year or less (Table 1). Teak plantations in the early days were established to complement, not replace, natural forests (Maung Maung Htwe, 2000). These plantations did not have a defined rotation period and after final thinning at age 40, were treated as a natural forest and managed under selection cutting (Maung Maung Htwe, 2000). Consequently, teak plantations at an age suitable for harvesting were only rarely been clear-felled, and a second rotation of taungya teak reforestation has only been undertaken very seldomly, if at all. Since the 1980s however, the area dedicated to teak plantations has increased drastically to more than 10,000 ha/year (Table 1) through projects financed by the Asian Development Bank and the World Bank (Saw Kelvin Keh, 1997). In the future, these extensive teak plantations will be harvested by clear felling and consequently, large scale second-rotation of taungya teak reforestation will have to be undertaken. Despite the long history of taungya teak reforestation in Myanmar, little quantitative research on the effect of the second rotation problem has been undertaken and consequently the future sustainability of the system should be examined closely.

Table 1. Teak plantation area in Myanmar, 1896 to 1998.

Period	Total area (ha)	Annual area planted (ha)
1896-1941	36,930	803
1942-1947	n.a.	-
1948-1965	2,459	137
1966-1970	6,067	1,213
1971-1975	4,425	885
1976-1980	13,037	2,607
1981-1985	53,665	10,733
1986-1990	58,950	11,790
1991-1995	53,308	10,662
1996-1998	37,813	12,604
Total	266,654	

Calculated from the data in Maung Maung Htwe (2000)

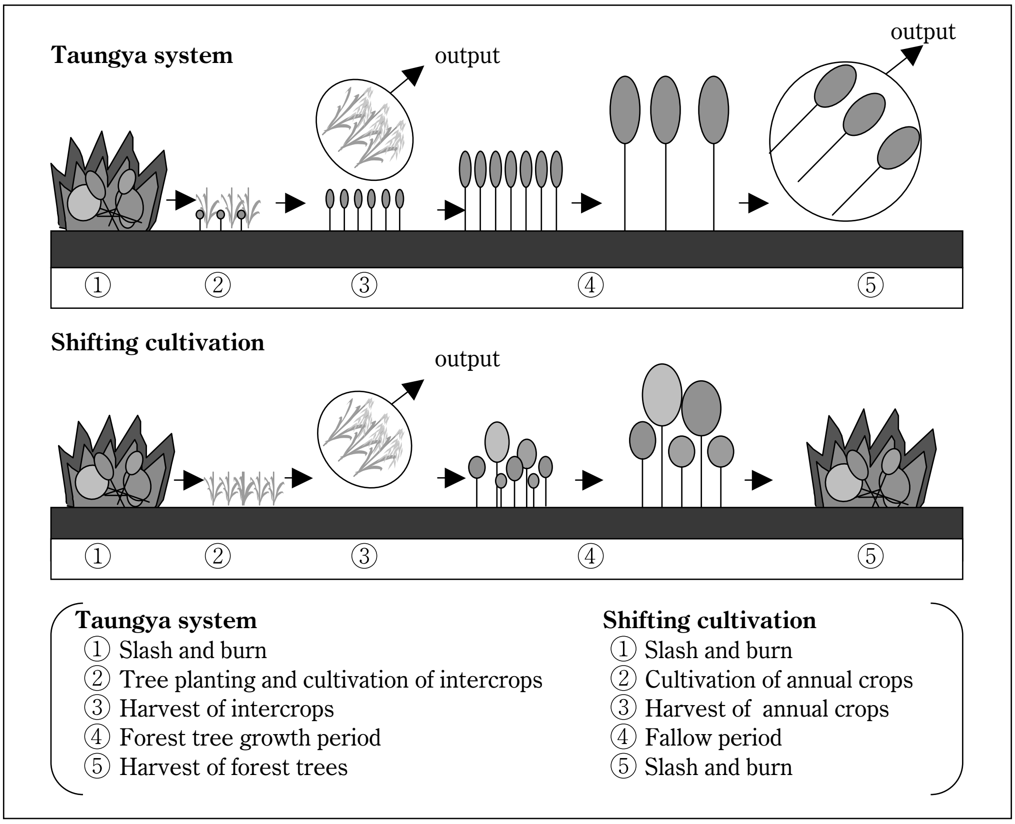


Fig. 1. Schematic process of taungya system and shifting cultivation.

To mitigate the second rotation problem, preservation of soil productivity during the teak growth period, phase ④ in Figure 1, is considerably important. In particular, the conservation of soil organic matter (SOM) is fundamental to sustainable forest soil management as SOM contributes to soil productivity through its positive effects on the chemical, physical and biological properties of the soil (Stevenson & Cole, 1999). This is particularly relevant in the tropics where many soils are poor in inorganic nutrients and rely on the recycling of nutrient from SOM to maintain fertility (Tiessen *et al*., 1994). Furthermore, many forest areas in Myanmar are susceptible to forest fires that occur frequently during the dry season (Myat Thinn, 2000; Saw Eh Dah, 2001). While these fires are not usually fierce, they are of sufficient intensity to burn the forest floor litter that is a main resource of SOM. The effect of forest fires should thus not be overlooked when considerations of SOM dynamics are made.

The aim of this study was to evaluate the long-term sustainability of taungya teak reforestation in Myanmar from the viewpoint of SOM conservation. The long-term changes in the soil carbon content of teak plantations were assessed using a chronosequence approach, in which soil carbon content in teak plantations of different stand ages was compared. We then examined the turnover of litter, a main source of SOM in forest ecosystems, to determine the relative contribution made by litter to soil carbon dynamics. Particular attention was given to the effect of forest fires on the dynamics of forest floor litter and soil carbon in teak plantations.

MATERIALS AND METHODS

Study Area

The study area is located in Oktwin township (Toungoo district, Bago division) on the eastern slope of Bago Yoma. Bago Yoma is a mountain range in the middle of Myanmar that forms a watershed between the Ayeyarwady and Sittoung river catchments. The maximum altitude of Bago Yoma is approximately 800 m above sea level. The pronounced north to south ridges are frequently precipitous and the spurs are generally undulating (Watson, 1923). Most of the area is composed of tertiary sandstones and shale (Watson, 1923) with soils that are classified as Ultisols. The soils are generally light textured and the clay content increases with depth to attain its maximum in the B horizon (Bender, 1983). The dominant forest type consists of mixed deciduous forests that are economically important because valuable trees, such as teak, Pinkado (*Xylia dolabriformis*) and other commercial species, are usually associated with these forests. Figure 2 shows the monthly precipitation, and mean monthly maximum and minimum temperatures (1993- 2002) at the Toungoo weather station (18°55’ N, 96°28’E) located about 15 km east of the foothills of Bago Yoma. Annual rainfall was 2214 mm and there are distinct rainy and dry seasons. Most rainfall occurred during the period of May to October, although there were several showers in April and November.

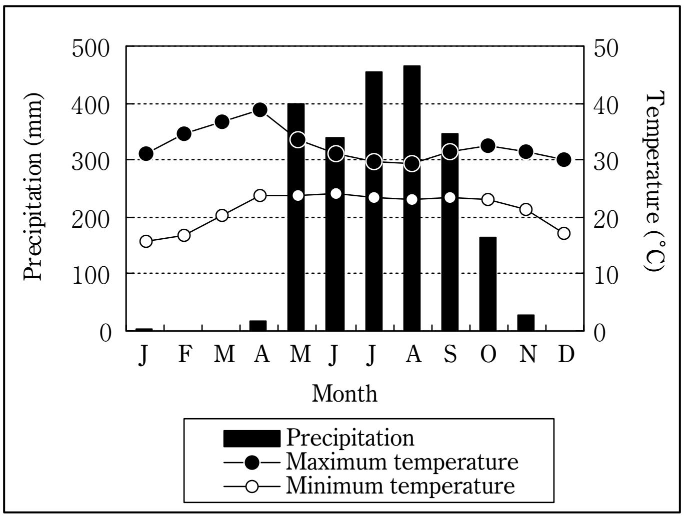


Fig. 2. Monthly precipitation and temperatures measured at Toungoo Weather Station (1993-2002).

Experimental Design

Establishment of experimental plots

Experimental plots were selected in the teak plantations of the Kabaung Reserved Forest and Bondaung Reserved Forest (18°42'−18°57'N, 95°51'−96°21'E) in Oktwin Township (Figure 3). In these Reserved Forests, teak reforestation has been practiced since 1884.

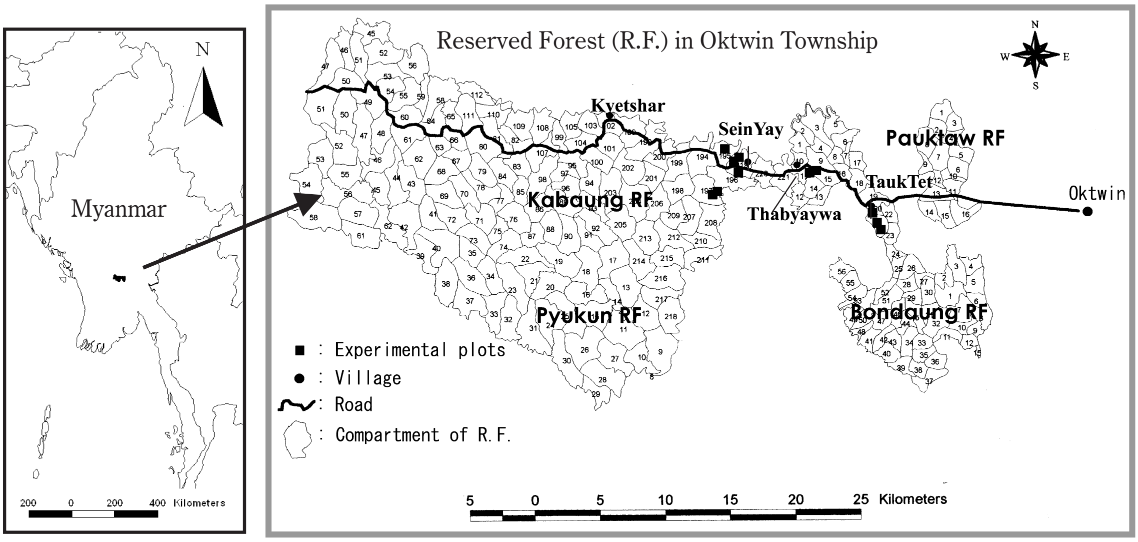


Fig. 3. Location of study area and experimental plots.

To assess the long-term soil carbon dynamics in teak plantations, experimental plots were selected from stands of different ages (0-96 years). The size of each experimental plot was 0.09 ha. General information for each experimental plot is shown in Table 2.

Table 2. General information for experimental plots.

Experimental plot no.	Stand age	Year planted	Slope aspect(°)	Slope direction	Reserved Forest (R.F.)
TP2002a	0	2002	11-34	N40°E	Kabaung R. F.
TP2002b	0	2002	21	S30°W	Kabaung R. F.
TP1998	4	1998	14-24	S44°W	Bondaung R. F.
TP1981a	21	1981	12-24	S14°W	Kabaung R. F.
TP1981b	21	1981	8-18	S14°E	Kabaung R. F.
TP1981c	21	1981	13-24	N54°E	Kabaung R. F.
TP1967	35	1967	20-34	S41°W	Bondaung R. F.
TP1966	36	1966	15-30	S24°E	Bondaung R. F.
TP1921	81	1921	8-24	S14°E	Kabaung R. F.
TP1906a	96	1906	14-32	S30°W	Kabaung R. F.
TP1906b	96	1906	10-26	S50°E	Kabaung R. F.

The year in which the plantation was established is given after TP (teak plantation) in the experimental plot name.

Soil sampling and physico-chemical analysis

Surface soil (0-5cm) was collected from all experimental plots in May 2002. Twelve surface soil samples were collected from each plot and 4 sets of samples were mixed together to make 3 composite samples. For the control samples, surface soil from natural teak bearing forests and secondary forests was also collected by the same method. In addition, to observe the change in soil properties during one rainy season, surface soil was re-sampled in November 2002 from 7 experimental plots.

All soil samples were air dried and passed through a 2mm sieve prior to the analysis of total carbon and nitrogen contents with an NC analyzer (Sumika Chem. Anal. Service, Sumigraph NC-800).

From every experimental plot, 3 core samples (100ml) were collected from the surface layer (0-5cm) to determine bulk density.

Production and decomposition rates of litter

To measure litter production in mature teak plantations, 20 litter traps made of plastic screens (2mm mesh) with surface areas of $0.5m^2$, were set up in TP1921. Litter in the traps was collected 1-2 times a month from February 2002 to January 2003. After measuring fresh weight, the litter materials were oven dried at 80℃ for dry weight determination.

To observe the litter decomposition rate, teak leaf litter was sampled in TP1921 and put into 30 bags made of plastic screen material (2mm mesh) after weighing. These bags were placed on the forest floor of TP1921 in February 2002 and 10 bags were collected in June and November 2002, and March 2003 and weighed. The litter materials were then oven dried at 80℃ for dry weight determination.

Coverage of teak leaf litter on the forest floor

To assess the condition of the forest floor litter at the beginning of the rainy season, the coverage of teak leaf litter (%) on the forest floor was determined in May 2002. This was achieved by dividing each experimental plot into 9 subplots, each measuring $10m^2$, and visually estimating the coverage of teak litter in each subplot.

RESULTS

Long-term change in soil carbon content in teak plantations

Total carbon content in the surface soil (0-5cm) of teak plantation stands of different ages (0-96 years) is depicted in Figure 4. As can be seen in the figure, soil total carbon in teak plantations did not accumulate with time and the carbon content fluctuated between 6.78-11.31 t ha^{-1} (or 1.04-1.81%) during teak growth period (stand age: 4-96 years). The soil carbon content observed during this period was significantly lower (P<0.01) than that observed during the intercropping period of taungya (stand age: 0 years).

Table 3 depicts the difference in soil total carbon content between teak plantations during the teak growth period and other forests types located in the vicinity. The secondary forests (bamboo dominant) listed in this table are often converted into taungya teak plantations and they could therefore be considered as representative of conditions before the teak reforestation in this area. As shown in Table 3, soil carbon content in teak plantations was significantly lower than that observed in natural teak forests and bamboo dominant secondary forests.

In addition, soil pH (H_2O) in teak plantations and the other forest types was 6.13±0.30.

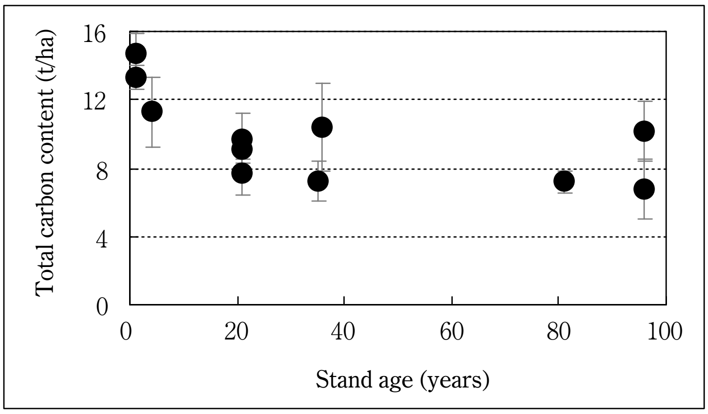


Fig. 4. Total carbon content in surface soil (0-5cm) from stands of different ages (0-96years) in teak plantations.

Table 3. Total carbon content of surface soil (0-5cm) in teak plantations and other forest types.

Forest type	Soil carbon content (%) in surface soil (0-5cm)
Teak plantations (during teak growth period)	**1.34** ± 0.35
Natural teak forests	****2.00** ± 0.31
Secondary forests (Tree species dominant)	**1.38** ± 0.10
Secondary forests (Bamboo dominant)	****2.38** ± 0.43

**: significantly higher (P<0.01) than teak plantations

Judging from the acidic condition of the soil in the present study area, soil total carbon content almost corresponds to soil organic carbon content.

Turnover of leaf litter in mature teak plantations

Monthly leaf litter production for the one-year period in TP1921 is shown in Figure 5. Teak leaf litter production (2.71 t ha^{-1}) accounted for 69.6 % of annual leaf litter production (3.89 t ha^{-1}). In addition, the amount of annual non-leaf litter such as branches, bark, flowers and fruits was 0.90 t ha^{-1}, which accounted for 18.7 % of annual litter production. Leaf litter production, especially teak leaf litter production, exhibited obvious seasonality (Figure 5). Most of the teak leaf litter produced occurred in the dry season, and 80.6 % of the annual teak leaf litter was produced from January to March.

Dry weight loss and annual decomposition rates of teak leaf litter after 13 months in TP1921 is shown in Figure 6. The annual decomposition rate constant k for TP1921 was calculated as 1.51 y^{-1} using the following formula (1) described by Olson (1963).

$$W/Wo = e^{-kt} \quad (1)$$

W : Weight of litter remaining after time t (g)
Wo : Initial weight of litter (g)
k : Annual decomposition rate constant

Figure 7 depicts the amount of teak leaf litter estimated to have accumulated on the forest floor in TP1921, with monthly teak leaf litter production given for reference. Given that the amount of litter that has accumulated on the forest floor is determined by the balance between the litter accession rate and the litter decomposition rate (O'Connell & Sankaran, 1997), the following formula (2) was applied to estimate the amount of forest floor litter at the end of each month. For

$$L_{fx} = \sum_{n=1}^{x} L_{pn} * e^{-k(x-n)/12} \quad (2)$$

L_{fx} : Amount of leaf litter that remained on the forest floor x month after the beginning of the defoliation period
L_{pn} : Monthly leaf litter production in the n_{th} month from the beginning of the defoliation period
k : Annual decomposition rate constant

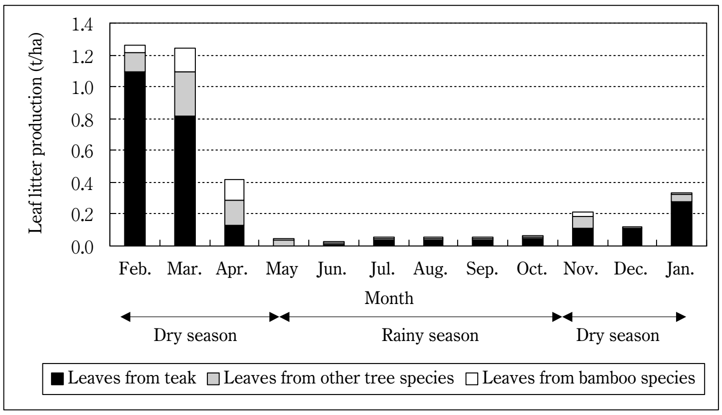
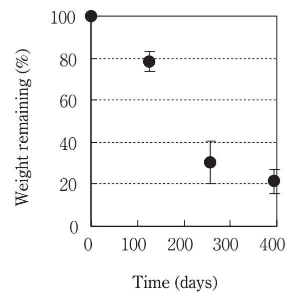


Fig. 5. Monthly leaf litter production (t/ha) in TP1921. (February 2002 to January 2003)



Annual decomposition rate constant k (y^{-1})	1.51 (r^2=0.93, P<0.05)
Weight remaining after 12 months (%)	22.6
Time required for decomposition (month)	
50%	5.6
95%	24.1

Fig. 6. Dry weight loss and decomposition rate of teak leaf litter under TP1921. (February 21, 2002 to March 21, 2003)

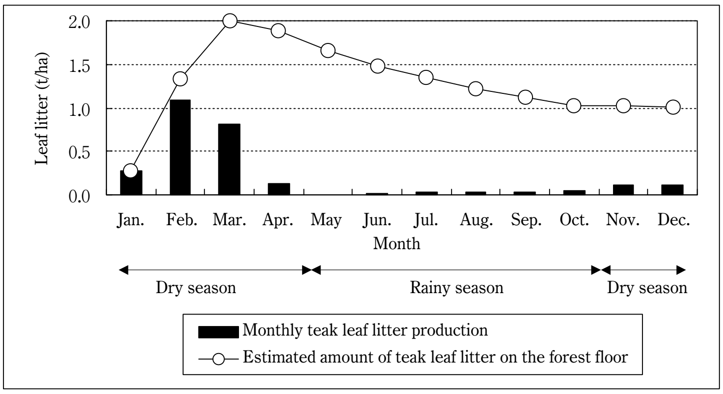


Fig. 7. Estimated amount of teak leaf litter accumulated on the forest floor under TP1921.

convenience, we took the beginning of the defoliation period January 1, and 1.51 was used as the annual decomposition rate constant k. In this formula, leaf litter produced in previous years was not considered. In Figure 7, a sharp increase in the estimated amount of forest floor litter was observed from January to March when the most of annual leaf litter was produced. At the end of March, the amount of estimated forest floor litter reached its highest levels (1.99 t ha^{-1}) before gradually decreasing with time. At the end of May, the beginning of the rainy season, the estimated amount of forest floor litter was 1.66 t ha^{-1}, and at the end of the one-year period in December, 1.01t ha^{-1} of teak litter (37.3 % of annual production) was estimated to have remained. The amounts of forest floor litter calculated for the end of March, May and December corresponded to approximately 27.1, 22.6 and 13.8 sheets/m^2 of teak leaves, respectively. For calculations requiring the dry weight of one leaf-litter sheet, 7.3 g, which was the actual measurement in TP1921, was substituted.

Coverage of teak leaf litter on the forest floor in teak plantations

Figure 8 depicts the actual coverage of teak leaf litter on the forest floor in May 2002 under all experimental plots, except TP2002a and TP2002b, as well as the occurrence of forest fire disturbance. As shown in this figure, no relationship was observed between the coverage of teak leaf litter and the stand age of teak plantations. These experimental plots can be divided into two groups:

Group 1: Without forest fire disturbance. Coverage of teak leaf litter was higher than 50% (3 experimental plots)

Group 2: With forest fire disturbance. Coverage of teak leaf litter was lower than 3% (6 experimental plots)

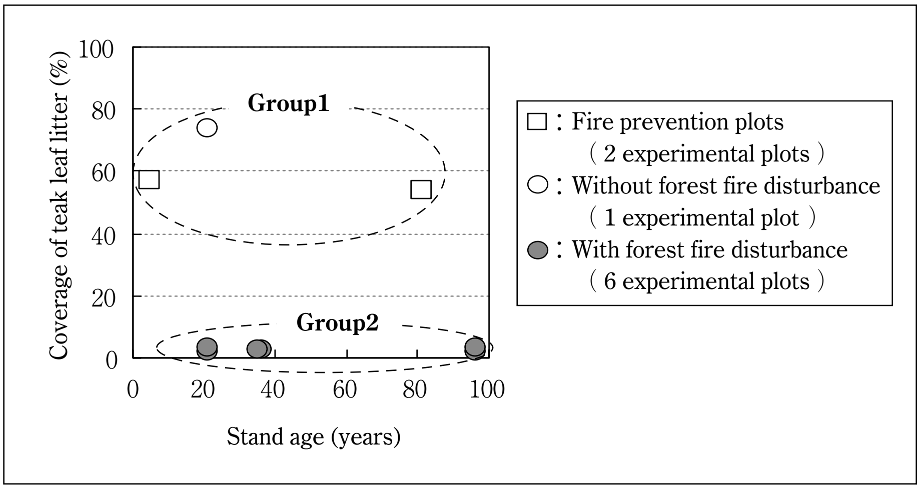


Fig. 8. Coverage of teak leaf litter on the forest floor at the end of May 2003 with fire disturbance history.

It must be noted that the coverage of teak leaf litter in experimental plots with forest fire disturbance was markedly lower than that observed in plots without forest fire disturbance. In addition, among Group 1, two experimental plots out of three were protected from forest fires by fire prevention measures during the dry season, while all experimental plots in Group 2 were not protected. So 85.7% (6 plots out of 7) of the experimental plots without fire prevention were disturbed by forest fires.

Changes in carbon content and C/N ratio of surface soil during one rainy season

Table 4a and 4b show changes in total carbon and C/N ratio in surface soil (0-5cm) during one rainy season in several of the Group 1 and Group 2 experimental plots, respectively. Of the experimental plots in Group 1 that were not disturbed by forest fires and had high coverage of teak litter, a significant increase ($P<0.05$) in C/N ratios during one rainy season was observed in TP1981c and TP1998. Moreover, a significant increase ($P<0.05$) in total carbon content was observed in TP1981c, which had the highest teak leaf litter coverage. Conversely, in the experimental plots of Group 2 that were

Table 4a. Change in total C and C/N ratios of surface soil (0-5cm) in Group 1 experimental plots during one rainy season (end of May to middle of November, 2002).

Experimental plot no.	Coverage of teak litter	Total C (%)		C/N ratio	
		End of May	Middle of November	End of May	Middle of November
TP1981c	**73.6%**	**1.44** ± 0.22	***1.63** ± 0.02	**12.7** ± 0.7	***13.9** ± 0.1
TP1998	**56.9%**	**1.81** ± 0.33	**1.92** ± 0.29	**13.2** ± 0.7	***14.3** ± 0.4
TP1921	**54.2%**	**1.05** ± 0.09	**1.21** ± 0.24	**12.0** ± 0.3	**12.8** ± 2.1

*significant increase during one rainy season ($p<0.05$)

Table 4b. Change in total C and C/N ratios of surface soil (0-5cm) in Group 2 experimental plots during one rainy season (end of May to middle of November, 2002).

Experimental plot no.	Coverage of teak litter	Total C (%)		C/N ratio	
		End of May	Middle of November	End of May	Middle of November
TP1966	**2.5%**	**1.70** ± 0.42	**1.66** ± 0.31	**14.9** ± 0.7	**14.7** ± 1.0
TP1967	**2.5%**	**1.06** ± 0.17	**1.05** ± 0.06	**10.8** ± 0.7	**10.6** ± 0.9
TP1981a	**2.3%**	**1.32** ± 0.08	**1.39** ± 0.27	**13.2** ± 0.5	**12.7** ± 0.8
TP1981b	**2.0%**	**1.14** ± 0.19	**0.97** ± 0.10	**11.8** ± 1.2	**10.9** ± 1.1

disturbed by forest fires and had lower coverage of teak litter, no significant change in these soil properties was observed.

Generally, the C/N ratio of fresh organic matter gradually decreases in the course of its decomposition. Higher C/N ratios therefore indicate a higher ratio of fresh organic matter in total SOM. Therefore, in two of the three plots where forest fires did not occur, and where teak leaf litter coverage was higher than 50%, the ratio of fresh organic matter was observed to increase during one rainy season.

Correlation between carbon content and C/N ratio of surface soil

Figure 9 depicts the relationship between total carbon content and the C/N ratio of surface soil (0-5cm). The data for teak plantations with stands in excess of 5 years is shown in Figure 9a, while that in natural teak forests and secondary forests are shown in Figure 9b. In teak plantations, a high positive correlation ($r^2=0.70$, $P<0.01$) was observed between total carbon content and C/N ratios. No significant relationship was observed between these two variables under natural teak and secondary forests.

These results suggest that where the SOM content was high, the ratio of fresh organic matter in SOM was also high in

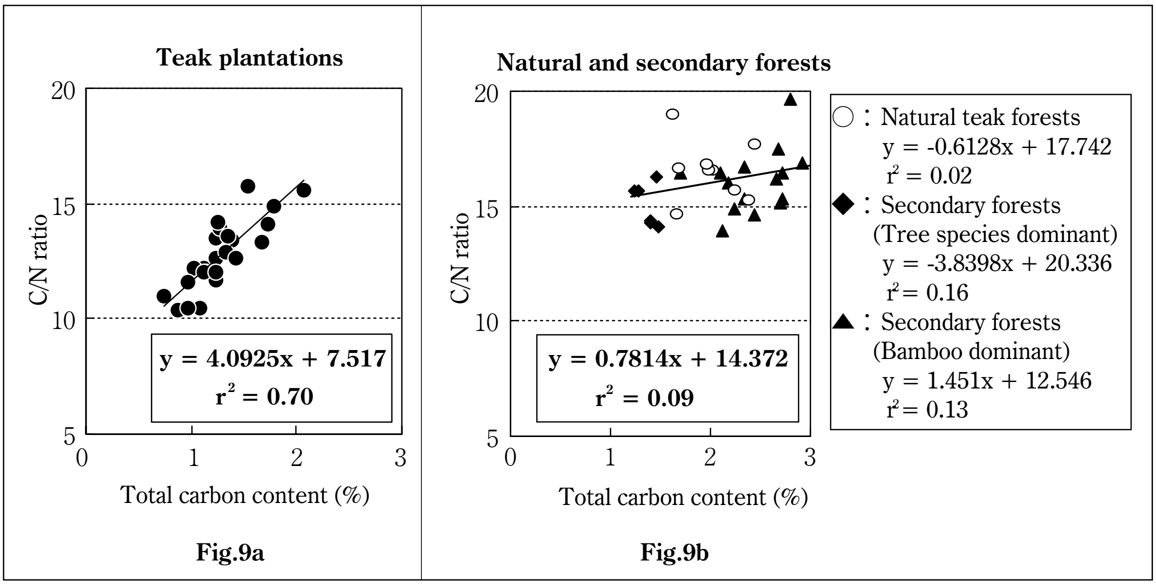


Fig. 9. Relationship between total carbon content and C/N ratio of surface soil (0-5cm).

teak plantations, whereas these two soil parameters were independent of each other in natural teak and secondary forests. In addition, the C/N ratio of surface soil in teak plantations was generally less than 15.0, and significantly lower ($P<0.01$) than that observed in natural teak and secondary forests. This suggests that the ratio of fresh organic matter in total SOM in teak plantations was lower than that of natural teak and secondary forests.

DISCUSSION

Is the soil carbon dynamics observed in these teak plantations a common phenomenon ?

In order to assess whether the long-term changes in soil carbon content observed in the teak plantations of this study (Figure 4) are representative of other plantations, it is important to understand general soil carbon dynamics in plantations. Although the dynamics of soil carbon after reforestation is a site-specific matter, influenced by factors such as climate, tree species, topography, parent material of soil, previous land use, site management and others, some general trends can be inferred from other review studies. Paul *et al*. (2002) reviewed 43 case studies concerned with the change in soil carbon after reforestation. These authors concluded that, on average, soil carbon in surface soil decreased by 3.46% per year relative to the initial carbon content during the first five years of reforestation. This was followed by a decrease in the rate of decline and eventually, recovery to original levels after approximately 30 years. Guo & Gifford (2002) reviewed 74 case studies concerned with the change in soil carbon after land use change. They concluded that if land use is converted from native forests to plantations, soil carbon stock was reduced by about 20% when the plantations were younger than 40 years, but original levels were restored in plantations over 40 years old. According to these reviews, there is an initial loss of soil carbon immediately after reforestation, but it recovers to original levels after a certain time (around 30-40 years).

In the present study, this initial loss of soil carbon after teak reforestation was observed (Figure 4), and thus correlated with the findings observed in these review studies. However, contrary to these studies, soil carbon content in these teak plantations did not recover to their initial levels - even after 96 years of reforestation. In addition, soil carbon content in teak plantations during the teak growth period was significantly lower than that observed in natural teak forests or bamboo dominant secondary forests (Table 3). Consequently, it is reasonable to suppose that the long-term change in soil carbon of the teak plantations observed in this study is an uncommon phenomenon among plantations in general.

However, if we consider only assessments of soil carbon in teak plantations, the decrease in soil carbon observed after reforestation is not unprecedented. Many case studies have reported that a decrease in soil carbon was observed after the conversion of natural forests into teak plantations (Table 5). Judging from these results, it seems likely that a decrease in soil

Table 5. Soil carbon content (%) of surface soil in teak plantations and adjacent natural forests in other case studies.

Soil carbon content (%) of surface soil		Age of teak plantations (years)	Study area	Reference
Teak plantations	Natural forests			
1.5 ± 0.16	1.9 ± 0.10	15	Nigeria	Aborisade and Aweto (1990)
1.70	3.20	± 20	India	Mongia and Bandyopadhyay(1992)
*11	*13	17～27	Ghana	Amponsah and Meyer (2000)
0.8	1.7	± 40	India	Prasad et al. (1985)
1.92	2.39	unknown	India	Balagopalan (1995)
1.34 ± 0.35	2.00 ± 0.31	4～96	Myanmar	Present study

* soil organic matter content (%)

carbon is a problem common to teak plantations, though soil carbon content in the teak plantations examined in these studies may recover in the future, as the stand ages of plantations in these studies were less than 40 years. In these studies however, the mechanism of soil deterioration was not discussed in detail and this should be examined more carefully for the future sustainability of teak reforestation.

In the following sections, we will discuss the main cause underlying the prevention of soil carbon accretion in the teak plantations in the present study area.

Effect of forest fires on the dynamics of forest floor litter

To better understand the long-term dynamics of SOM in teak plantations, the dynamics of litter need to be considered first, because SOM builds up as a result of plant litter production (Tiessen & Shang, 1998) and the quantity of SOM in forest ecosystems is a result of the balance between the input of plant litter and loss due to the decomposition of soil carbon over time (Turner & Lambert, 2000; Liski *et al*., 2002). The dynamics of leaf litter were examined in detail in this study as it contributes more than 80% to total annual litter production.

In the present study, there was a marked disparity between the estimated values and the actual values obtained for amounts of forest floor litter. At the end of May, the estimated amount of teak leaf litter in TP1921 was 1.66 t ha^{-1} (Figure 7), or 22.6 sheets/m^2 of teak leaves. Conversely, actual coverage of teak leaf litter on the forest floor with fire disturbance was less than 3%, or approximately less than 1 sheet/m^2 of teak leaves, whereas that without fire disturbance was higher than 50 % (Figure 8). These results suggest that the teak leaf litter that accumulated on the forest floor was burnt by forest fires and almost completely disappeared by the end of May. From observations made since the 19th century, forest fires in Myanmar are merely surface fires that burn slowly as they advance and consume the dry leaves on the forest floor (Slade, 1896). While such fires are not fierce, they are of sufficient magnitude to burn forest floor litter completely. In addition, the high percentage of fire disturbance in the experimental plots without fire prevention measures (85.7%) suggests a high frequency of forest fires.

Furthermore, overlapping of the forest fire period and the teak defoliation period is a critical problem. The fire-hazardous period in Myanmar normally lasts for about four months, from mid-January to mid-May (Myat Thinn, 2000) with frequent fires at the end of the dry season. Concomitantly, the main defoliation period for teak occurs from January to March and 80.6% of the annual teak litter was produced during these 3 months (Figure 5). It is therefore quite likely that the forest fires that occur during the teak defoliation period would easily consume a large proportion of the annual litter production. Figure 10 depicts the effect of the timing of forest fires on the amount of forest floor litter. This figure shows the estimated amount of teak leaf litter on the forest floor under the following 3 conditions: no fire hazard throughout the year (control, shown in Figure 7), fire disturbance at the end of January, and that at the end of April. For the estimation of the amount of forest floor litter, formula (2) was applied with the assumption that forest fires consumed all of the forest floor litter at the moment of the fire disturbance. From Figure 10 we can infer that, if forest fire were to occur at the end of January, there would be little effect on the amount of forest floor litter compared to the control. However, a forest fire at the end of April, or at the end of the dry season, would greatly decrease the amount of forest floor litter throughout the year.

Consequently, it would thus seem that frequent forest fires at the end of the dry season interrupt the leaf litter supply to the soil in teak plantations.

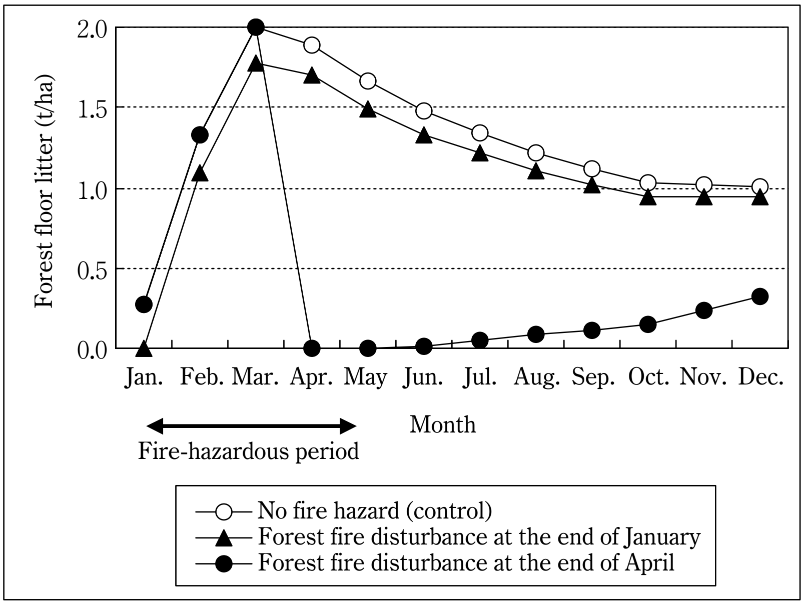


Fig. 10. Effect of the timing of forest fires on the estimated amount of teak leaf litter accumulated on the forest floor under TP1921.

Do the forest fires prevent the accretion of soil carbon?

The next important question is whether the absence of forest fire disturbance, allowing almost all of the annual leaf litter produced to be supplied to the soil, would result in increased soil carbon in teak plantations over time.

In TP1921, 2.71t ha^{-1} of teak leaf litter was supplied to the soil and 1.01 t ha^{-1} of that remained on the forest floor (1.70 t ha^{-1} decomposed) in one year (Figure 7). Humus, the main component of SOM, is formed during the litter decomposition process through the activity of microorganisms (Chertov & Komarov, 1997; Berg & McClaugherty, 2003) and it is generally accepted that stable components of organic matter, such as humus, persist in soil for a few years, decades or longer (Theng *et al*., 1989; Stevenson & Cole, 1999).

Of particular importance, is the proportion of the carbon contained in litter that is converted into humus. According to Nye & Greenland (1960), the proportion of fresh organic matter that is converted to soil humus is probably between about 10-20% of the total, and the remainder is lost through oxidation. For teak litter, Prasad *et al*. (1991) incubated finely powdered oven-dried teak leaves thoroughly mixed with soil in plastic pots and observed that approximately 10.9-13.0% of the initial teak-leaf carbon was converted into humus-carbon after 12 months of incubation (Table 6).

Table 6. Changes in the humus content of soil samples with varying initial amounts of teak leaf material after 12 months of incubation.

Treatment	T1 (control)	T4 (2% leaf)	T5 (5% leaf)
Initial mass of teak leaves (g) in 1kg soil	0g	20g	50g
Initial mass of teak leaf-C (g) in 1kg soil (Carbon content in teak leaves: 41.4%)	0g	8.3g (L_1)	20.7g (L_2)
Humus-C content (%) after 12 months incubation	0.15% (a)	0.24% (b_1)	0.42% (b_2)
Net increase in humus-C (g) per 1kg soil **$(b_n$-a)/100×1000**	–	0.9g (H_1)	2.7g (H_2)
Ratio of humus-C to initial litter-C (%) **H_n/L_n×100**	–	10.9%	13.0%

Incubation conditions: room temperature, soil water content of 35% (w/w)

Calculated from data in Prasad *et al* (1991)

Given that the proportion of litter carbon that is converted to humus is correlated with the initial chemical composition of litter (Berg & McClaugherty, 2003), it is reasonable to suppose that the ratio of teak leaf litter carbon converted into humus observed in the study of Prasad *et al*. (1991) is similar to that in the present study area. If we apply the same conversion ratio as that observed by Prasad *et al*. (1991) to the following formula (3), the potential amount of humus-carbon that could be formed from the 2.71t ha^{-1} of annual teak leaf litter produced would be approximately 0.14 t C ha^{-1}. In this estimation, 12.0 % (mean of 10.9 and 13.0 %) and 41.4 %, which were observed by Prasad *et al*. (1991), were substituted for

$$H = L * m * C_L/100 \quad (3)$$

H : Potential amount of humus carbon that can be formed from a given amount of leaf litter (L)
C_L : Carbon content in leaf litter (%)
m : Ratio of leaf litter carbon converted into humus (%)

m and C_L, respectively. Figure 11 depicts the effect of forest fire on humus formation in TP1921. In this figure, the following formula (4) was applied to estimate the potential amount of humus carbon which could be formed from forest floor litter under the following two conditions: no fire hazard throughout the year (control) and fire disturbance at the end of April. For m and C_L, 12.0 % and 41.4 % were substituted, respectively. As before, the beginning of defoliation period was taken to be January 1, and we assumed that forest fire burned all of the forest floor litter at the time of the fire disturbance. From Figure

$$H_x = \sum_{n=1}^{x} L_{pn} * m * C_L/100 \quad (4)$$

H_x : Potential amount of humus carbon that can be formed from the accumulated leaf litter on the forest floor x month after the beginning of the defoliation period
L_{pn} : Monthly leaf litter production in the n_{th} month from the beginning of the defoliation period
C_L : Carbon content in leaf litter (%)
m : Ratio of leaf litter carbon converted into humus (%)

11, it can be seen that fire disturbance at the end of April would largely decrease the potential amount of humus carbon in the forest floor litter at the end of December from 0.14 t C ha^{-1} (control) to 0.02 t C ha^{-1}. These results suggest that forest fire disturbance at the end of the dry season would largely interrupt humus formation in teak plantations.

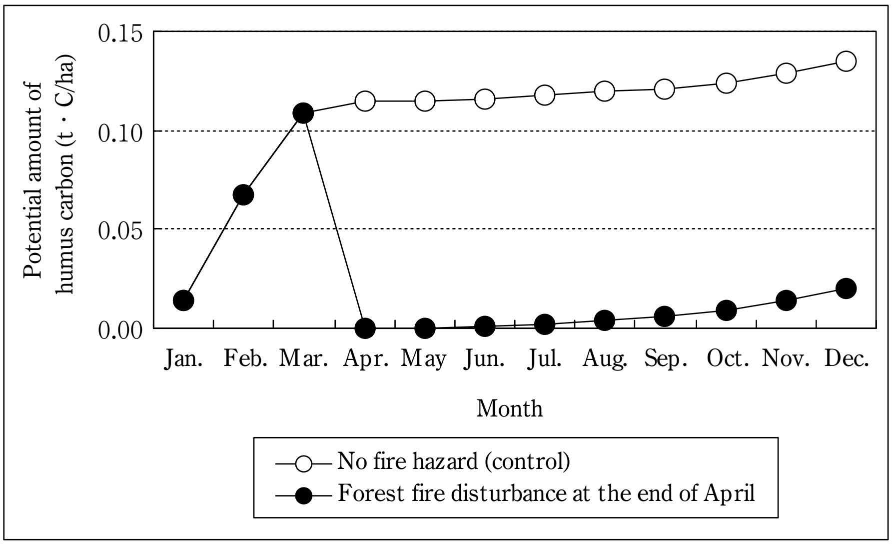


Fig. 11. Effect of forest fire on the potential amount of humus carbon on the forest floor under TP1921.

However, the occurrence of forest fires does not necessarily lead to a decrease in soil carbon content. Important factors that affect the dynamics of soil carbon as they relate to fire disturbance are the intensity and frequency of the forest fires (Pritchett & Fisher, 1987; Tiedemann *et al*., 2000; Johnson & Curtis, 2001). Generally, a high frequency of forest fires may lead to a decrease in soil carbon (Bird *et al*., 2000; Tiedemann *et al*., 2000), but the effect of fire intensity is difficult to assess. Johnson & Curtis (2001) reviewed 48 observations of the effect of forest fires on soil carbon content and found that it decreases following prescribed, low intensity fires (similar in intensity to those that occur in the present study area), whereas soil carbon content was found to increase after high intensity wildfires. However, conflicting results have also been reported in other studies (Groeschl *et al*., 1991; Johnson, 1992). Increase in soil carbon following forest fires may have been caused by incorporation of unburned residues, including charcoal, into soil (Johnson & Curtis, 2001), while its decrease may be caused by the loss of organic resources due to exhaustion of the litter. Long-term dynamics of SOM is thus be determined by the balance of these two contrary effects of forest fires. However, even in instances of increased soil carbon following forest fires, the net amount of carbon in the forest floor-soil ecosystem does not increase at all, because the increase in soil carbon after forest fires arises mainly from the transfer of unburned organic matter from the forest floor into the soil. Even so, assuming that forest fires promote the decomposition of forest floor litter and thus aid the transfer of organic matter into soil and promote SOM formation, this effect is unlikely to be significant in tropical climates where decomposition rates of litter is generally high.

Consequently, it seems reasonable to assume that forest fires inhibit soil carbon accretion in the teak plantations of the present study area.

Effect of forest fires on the total carbon content and C/N ratio of surface soil

From what has been discussed above, it is possible to establish the following two hypotheses:

Hypothesis Ⅰ: If teak plantations are not disturbed by forest fires, both total carbon and C/N ratios of surface soil increase in the short term, because fresh organic matter is supplied and incorporated into the soil.

Hypothesis Ⅱ: If teak plantations are continuously disturbed by forest fires, both total carbon and C/N ratio of surface soil gradually decrease, because the supply of fresh organic matter is interrupted and the original stock of SOM gradually decomposes with time.

We will examine these hypotheses from the following two viewpoints: the short-term effects of forest fires during one rainy season, and long-term effects of forest fires throughout the teak growth period.

Short-term effects: Changes in total carbon and C/N ratio after one rainy season

The results shown in Table 4a and 4b indicate the short-term effects of forest fires on the total carbon content and C/N ratio of surface soil. The fact that a significant increase in total carbon and C/N ratios was observed in some experimental plots without forest fire disturbance (Table 4a) partly supports hypothesis Ⅰ, even though no significant change was observed in TP1921. One possible reason why a significant increase in total carbon and C/N ratios was not observed in all experimental plots without fire disturbance could be the heterogeneity of litter distribution. In TP1998 and TP1921, where the increase of total carbon content was not significant, teak litter coverage was only about 50%, or about half the area of the forest floor was not supplied with leaf litter. Due to the heterogeneity of leaf litter supply, total carbon and C/N ratios of soil after one rainy season exhibited high standard deviations, and consequently, no significant increases were detected.

Conversely, the absence of a significant increase in soil carbon and C/N ratios in the experimental plots with forest fire disturbance (Table 4b) suggests that the forest fires interrupted the supply of fresh organic matter to the soil. However, a significant decrease in these soil properties was also not observed in these experimental plots, probably because the decomposition rate of SOM, especially that of humus, is too slow to be detected within one rainy season. If these plots are continuously disturbed by forest fires at the end of dry season for many years, a significant decrease in both soil properties would be detected and hypothesis Ⅱ would hold true.

Long-term effects: Correlation between total carbon content and C/N ratio

Figure 9 indicates the long-term effects of forest fires on the total carbon content and C/N ratio of surface soil. The strong positive correlation ($r^2 = 0.70$, $P < 0.01$) between total carbon content and C/N ratio of surface soil in teak plantations (Figure 9a) can be interpreted as follows. Given that the frequency of forest fires in the present study area is high, total carbon and C/N ratios of the soil would be low and gradually decrease with time due to an interruption in the supply of fresh organic matter (as mentioned in hypothesis Ⅱ). Conversely, these soil properties would increase if forest fires did not occur by chance (as mentioned in hypothesis Ⅰ). Consequently, where the total carbon content is high, the C/N ratio is also high and vice versa in the long run. Meanwhile, fire prevention in teak plantations is practiced for 5 consecutive years after reforestation in Myanmar (Maung Maung Htwe 2000). To control for the effect of fire prevention we did not report the data obtained from teak plantations younger than 5 years old (e.g. TP1998) in Figure 9a. To evaluate the effect of fire prevention on the soil properties, we superimposed the data for TP1998 on the graph in Figure 9a (Figure 12). The regression lines in Figures 9 and 12 are the same, with the data from TP1998 deviating to the lower right of the line. The deviation observed in TP1998 can be attributed to the effect of fire prevention on facilitating the accumulation of SOM from the continuous supply of fresh organic matter, while the C/N ratio of accumulated SOM would gradually decrease with the continuation of decomposition.

These results lead us to the conclusion that the long-term dynamics of SOM in teak plantations in which fire prevention is practiced (e.g. TP1998) are different from teak plantations that are burned frequently. If all of the experimental plots had managed to escape forest fires continuously, soil carbon and C/N ratio would not exhibit a strong positive correlation. It therefore seems reasonable to conclude that frequent forest fires are responsible for the strong positive correlation observed between carbon content and C/N ratio of surface soil.

Conversely, no correlation was observed between the carbon content and C/N ratio in natural teak and secondary forests (Figure 9b). In these forests, the frequency of disturbance from forest fires would be as high as that observed in the

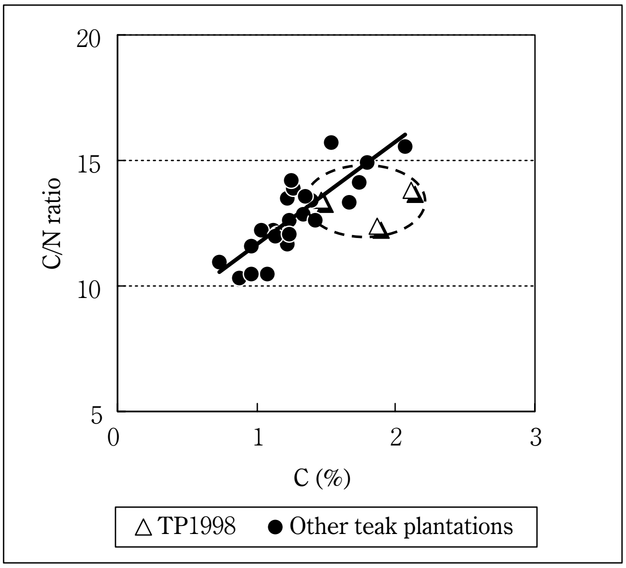


Fig. 12. Relationship between total carbon and C/N ratio of surface soil (0-5cm) in TP1998 and other teak plantations.

teak plantations. However, given the species richness of these forests, a certain amount of additional litter would be supplied to the soil, because the defoliation period of other species would not overlap entirely with the forest fire period. Compared to the teak plantations, the significantly higher C/N ratios of surface soil observed in these forests indicate a greater supply of fresh organic matter. If sufficient fresh organic matter is supplied continuously, soil carbon would increase with time, but C/N ratios would not be expected to increase in the long term as material would decompose over time, as observed in TP1998. Consequently, no correlation was observed between these soil properties and we conclude that the impact of forest fires on the dynamics of SOM is lower in natural teak and secondary forests than it is in teak plantations.

CONCLUSION

In the present study area, accretion of SOM in teak plantations was not observed, even 96 years after reforestation. One of the main factors that inhibited the accretion of SOM was the combustion of forest floor litter - a main resource of SOM - by forest fires. As the forest fire period overlaps the defoliation period of teak, most of the teak litter that had accumulated on the forest floor was easily burnt. The strong positive correlation observed between total carbon content and C/N ratio of surface soils in teak plantations suggests that forest fires have a marked affect on the soil carbon dynamics in teak plantations over time.

These results lead us to the conclusion that forest fires have detrimental effect on the long-term sustainability of taungya teak reforestation, because recovery of soil productivity during the teak growth period is crucial to the successive rotation of taungya teak reforestation.

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