Evaluation of the sustainability of a logging system consisting of selective logging and line planting in Indonesia

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Summary

Chapter 1

The forest cover in Indonesia is decreasing due to the logging and poor regeneration of dominant dipterocarp species. The resulting drop in productivity from desired species creates forests with low commercial value and induces land-use changes. Therefore, to maintain the forest area, it is important to preserve the level of productivity by desirable *Shorea* species (Dipterocarpaceae family). To promote the regeneration of desirable species, reduced-impact logging (RIL) and an enrichment line planting system have been installed in some forest areas; however, their effectiveness has not been evaluated. In this study, we assessed the efficiency of RIL and a line planting system for the regeneration of useful species in a logged-over forest.

This study was conducted in an active logging concession in Central Kalimantan, Indonesia. In this concession, both RlL and a line planting system have been in use since 1999.

Chapter 2

Stand dynamics after conventional logging (CL), reduced-impact logging (RIL), and RIL followed by enrichment line planting and annual slashing (RIL+LP/S) were monitored for 10 years in three plots (1 ha each) in each of the three sites in the concession. All trees >10 cm diameter at breast height

(DBH) and all planted *Shorea johorensis* were monitored for survival and growth. The rate of natural recruitment of poles (i.e., trees >10 cm DBH) of *Shorea* spp. was low in the CL site, intermediate in the RIL site, and high (46±29.5 trees/ha) in the RIL+LP/S site. The growth of non-planted trees followed the same trend, presumably due to the proliferation of pioneer trees in the CL site and lack of slashing and line clearing in the RIL site. Ten years after treatment, 78% of the planted seedlings were still alive. Although line planting increased the stock of desirable *Shorea* spp. relative to RIL alone, the enhanced light conditions brought about by strip cutting for line planting and the slashing of non-commercial understory plants and lianas increased natural regeneration significantly. To ensure sustainable productivity, either line planting or slashing would be appropriate in logged-over forests. In terms of cost, line planting is recommended to enhance the recruitment of commercially desirable species. The selection of an appropriate silvicultural treatment should depend in part on the post-logging abundance of desirable species and the costs associated with line planting and slashing.

Chapter 3

The large canopy opening and high light conditions in logged-over forests promote invasion by pioneer species and reduce the commercial value of the forest area. In the study site, reduced impact logging (RIL) has been applied to mitigate the effects of logging, and line planting of useful species has been conducted. However, quantitative assessments of canopy openness in response to RIL and line planting are lacking.

At the study site, 3-m wide strip cutting lines were implemented. The effects of this practice on canopy openness are poorly understood. This study assessed the effects of different logging systems on light conditions using hemispherical photographs taken in plots set in a primary forest, a forest logged using RIL, and a forest treated with strip cutting after RIL. Photographs were also taken at the center of the strip cutting lines. A comparison of canopy openness among the natural forest and two logged-over forests subjected to different logging treatments revealed that logging activity had significant effects on the light conditions in the area. High levels of canopy openness were found along skid trails and logging gaps following the trails. Therefore, reducing the impact on light conditions should be considered when planning skid trails. There was no significant difference in mean canopy openness between the logged-over forest plots with and without strip cutting lines; however, strip cutting affected the sunfleck duration on the forest floor. This could impact seedling recruitment under different light conditions in selectively logged forests. In addition, there were large differences in canopy openness along each line, which could cause variation in the growth of planted trees.

Chapter 4

We monitored the changes in light conditions among a primary forest and two managed forests with or without line planting after reduced-impact logging (RIL). In the study site where line planting was applied, the correlation between light conditions and line-planted seedling growth was assessed. Light conditions were monitored by hemispherical photography for 31 months immediately after logging and strip cutting for line planting. The locations were classified as skid trails, logging gaps, and planting lines. After logging, the canopy openness (CO) increased in both of the managed forests (significant differences were not found between the two sites). For each disturbance element, greater CO was detected in the skid trails and logging gaps than in the planting lines. After 31 months, the mean CO in each managed site decreased significantly due to pioneer seedling establishment. Invasion by pioneer species inhibited planted seedling growth. Additionally, there was a significant difference between the two sites managed by line planting 31 months later. Although the CO value in the logging gap and skid trail decreased to the value in the location protected from logging, the CO values in the planting lines were higher than the values obtained from the skid trails and logging gaps. Therefore, setting planting lines may influence forest dynamics by maintaining CO.

Chapter 5

Enrichment line planting of valuable *Shorea* species has taken place in logged forests to sustain the timber yield. However, scant information is available regarding the effectiveness of this method. Neighboring trees along planting lines may compete with and affect planted trees. We assessed the survival, growth, and crown exposure of planted trees to evaluate the effect of neighboring trees in three (1 ha) plots in which *Shorea johorensis* seedlings had been planted in strips 3 m wide and 5 m apart along five parallel north-south lines separated by 25 m each. The planted trees were monitored for 11 years after planting. Crown exposure was evaluated using a three-dimensional spatial model with *SExI-FS* software. Eleven years after planting, 77.6% of the planted *S. johorensis* had survived. The average diameter at breast height (DBH) was 16.7±5.6 cm (range, 5.3–33.6 cm). The initial growth 1 year after planting predicted the variance in DBH 11 years later. Trees showing rapid initial growth exhibited higher survival and growth rates in subsequent years. The variation in light conditions in the planting lines affected the initial and subsequent growth and survival rates. The spatial model illustrated how neighboring tree crowns suppress the growth of planted trees by casting shade. In a line planting system, neighboring trees affect the survival and growth of planted trees; however, this can be reduced by treating the canopy to ensure the exposure of planted trees to sunlight.

Chapter 1 General Introduction

Forest loss in Indonesia

In tropical Southeast Asia, the forest area is decreasing at an alarmingly rate (FAO 2010; Hansen et al. 2009). In the area, the forest loss was 0.6 million ha from 2000 to 2008 (Broich et al. 2011). One of the main causes of the forest loss is the failure of logging management (Ashton and Kettle 2012; Zimmerman & Kormos 2012). The logging management is mainly conducted in the lowland dipterocarp forests widely found in Southeast Asia (Ashton 1988; Whitmore 1990). In the forest, dominant tree species belong to Dipterocarpaceae; they compose the main canopy layer and account for ca. 20% in tree density and 50% in basal area (trees > 10 cm DBH).

In the lowland dipterocarp forest, selective logging is the most common type of forestry practice (Sist et al. 1998; Sist, Fimbel, et al. 2003; Imai et al. 2012). The desirable timber species are mainly dominant dipterocarps, especially species in the genus *Shorea* species with "light red meranti" wood (Ng et al. 2009).

The overexploitation of those meranti timber species and the associated reduction in seedling recruitment have led to the degradation and poor regeneration of forests. After the logging disturbance, pioneer species often invade the logged forest (Slik et al. 2002). Harvests of dominant dipterocarps followed by invasion of pioneers change the species composition, deplete timber stock and degrade the economical value. Low commercial-value secondary forests resulting from such practices are more likely to be abandoned or converted to agricultural land, and this process constitutes the main cause of forest loss in Southeast Asia (Sist and Nguyen-Thé 2002; Putz et al. 2008). In Indonesia, the Island of Borneo, the residual forest areas are still managed as production forests and the risk of sever degradation in high (Fig. 1-1).

Light demanding characteristics of commercial *Shorea* species and the gap dynamics in the lowland dipterocarp forest

Conventional selective logging causes extensive damage to the forest (Uuttera et al. 2000; Sist et al. 2003; Berry et al. 2008). For one, canopy opening by logging activities changes the light condition of the forest stand.

Light conditions in a forest floor determine seedling establishment and growth and survival of residual trees (Denslow 1987). In and around gaps, many species respond to the change in light conditions according to their biological characteristics (Romell et al. 2009). The commercially important meranti species (e.g. *S. leprosula, S. parvifolia* and *S. johorensis*) are light-demanding members of the family Dipterocarpaceae (Clearwater et al. 1999; Phillips et al. 2002). Those seedlings establish relatively shaded environment called "chimney environment" (Tuomela et al. 1996), and become to require high light intensity towards their maturity (Mauricio, 1987, Kenzo et al. 2011; Hattori, Tanaka, et al. 2013). In general, after heavy disturbance and dramatic light change by logging, *Macaranga* spp., which are primary pioneer species (Slik et al. 2002; Slik et al. 2003), may invade and dominate after logging disturbance (Pinard & Putz 1996; Romell et al. 2008). The post-logging invasion and dominance of pioneer species in disturbed forest inhibit the regeneration of dipterocarps.

Trials for sustainable forest management in Indonesia

The continued loss of tropical forests has focused on the conservation of residual primary forests. To protect the primary forest from logging management, it is urgent to identify forest management options that enable the repeated timber harvesting (Fredericksen & Putz 2003).

In Southeast Asia, the sustainability of timber harvests depends on the post-logging regeneration of desirable meranti species.

In recent years, the reduced-impact logging (RIL) method has been used to mitigate the impact of unplanned conventional logging on the forests (Lagan et al. 2007; Putz et al. 2008), with an expectation to ensure a better post-logging regeneration of dipterocarps. RIL was found to benefit the structure of residual stands, tree species diversity, and the soil through the use pre-logging mapping and planning to minimize damage from skidding, in combination with cutting of lianas and directional felling to minimize the secondary disturbance by felled trees (Pinard & Putz 1996; Bertault & Sist 1997; Pinard et al. 2000; Sist et al. 2003; Imai et al. 2012; Putz et al. 2012).

In Indonesia, the application of reduced-impact logging techniques (RIL) has been widely advocated in recent years (Pinard & Putz 1996; Bertault &

Sist 1997; Lagan et al. 2007; Medjibe et al. 2011; Putz et al. 2008; Putz et al. 2012; Imai et al. 2014).

However, in the lowland dipterocarp forest, the effectiveness of RIL for sustainable timber production is controversial (Fredericksen & Putz 2003; Sist & Brown 2004; Putz et al. 2008). An adequate level of disturbance, rather than minimal disturbance, may better stimulate the growth and recruitment of meranti species because of their light demanding characteristic. Mitigating logging impact by RIL may suppress the regeneration of commercial *Shorea* species and require the long time for the regeneration.

In eastern Borneo, Sist et al. (2003) estimated that a 40-year logging rotation with a harvest of 40 m^3/ha using RIL would maintain the natural regeneration potential of a forest. Even using RIL, a longer 80- or 100-year logging cycle is recommended to sustain the productivity from natural regeneration in North Borneo (Huth & Ditzer 2001). RIL methods originally designed to minimize the impacts of logging may not guarantee a sustainable timber yield (Putz et al. 2008). The typical forest management, by selective logging without any post-logging treatments will result in the depletion of the timber productivity. The post-logging natural regeneration of desirable timber species would be insufficient under repeatable harvesting.

To sustain the economical value of forest, some post-logging treatments are recommended to promote the regeneration of meranti species (Sist, Fimbel, et al. 2003; Sist & Ferreira 2007). To enhance stocking of desirable species, enrichment planting is promoted as a method to restore degraded forests

(Appanah and Weinland, 1996; Weinland 1998; Kettle 2010), and to ensure the sustaining timber yield in logged-over forest (Schulze 2008; Edwards et al. 2009). In Indonesia, enrichment line planting (LP) of seedlings of commercial timber species along cleared lines has been experimentally introduced. The LP treatment has been promoted by the Indonesian Ministry of Forestry (MoF) as Tebang Pilih Tanam Jalur (TPTJ) or selective logging and line planting system (Sève 1999; Chandrasekharan 2005; pamoengkas 2010).

The commercially important meranti species (e.g., *S. leprosula* and *S. johorensis*) typically used in TPTJ because of their light-demanding characteristic. Seedlings are planted in strip cutting lines opened in selectively logged forest. Strip cutting is conducted to allow sunlight to reach planted seedlings to enhance growth.

This method is expected to be useful in sustainable forest management, but knowledge about the line planting method is still limited (Ramos and del Amo 1992, Ådjers et al. 1995; Kammesheidt et al. 2003).

In addition, in TPTJ system, the planting lines were set in logged-over forest. Strip cutting for planting induces further disturbance to logged over forests. Therefore for line planting system, it is important to assess both the efficiency for the regeneration of desirable species and the impact on the logged-over forest.

Objective of this doctoral thesis

As introduced above, the logging system composed by selective logging and line planting has been not evaluated in terms of the sustainability. The purpose of this study is the evaluation of the sustainability of the forest management system composed of selective logging and line planting. The sustainability was evaluated from the efficiency for the regeneration of desirable species.

To achieve the purpose, in Chapter 2, I compared 10-year post-logging dynamics under different logging systems, conventional logging, RIL and RIL with line planting, in order to assess the effectiveness of RIL and line planting. And in Chapter 3 and 4, I focus on the light condition in the planting lines for the improvement of the methodology of line planting system. Based on the results from light condition assessment, in Chapter 5, I evaluated the effects of neighboring trees along the planting lines on the planted trees from the assessment of the planted trees' crown condition in in the canopy.

Research site description

This study was conducted in the 147,600 ha logging concession of PT. Sari Bumi Kusuma (SBK) in a lowland dipterocarp forest in Central Kalimantan, Indonesia (Fig. 1-2; 00°36'–01°10'S, 111°39'–112°25'E). The topography is gently undulating. Mean annual precipitation was 3240 mm according to measurements in the concession area, but ranged 2685 - 3902 during 2001-2009.

The concession right was contracted for 1999 - 2068. The concession has been FSC-certified as the sustainable forest management.

Indonesian forestry regulations frequently change (Ruslandi et al. 2014), but SBK currently works towards a 25-year harvest cycle with a focus on several Shorea species (e.g., *Shorea leprosula, S. johorensis, S. macrophylla, S. johorensis*...) and other commercial species including other dipterocarps (Shorea spp., Hopea spp., Dipterocarpus spp. and Vatica spp.). Other non-dipterocarps tree species, *Litsea firma* (Lauraceae), *Koompassia malaccensis* (Fabaceae), *Cratoxylon sumatranum* (Guttiferae) and other species are also harvested. However, 50-60 % of the timber volume harvested is from light demanding *Shorea* species. Meranti species are economically most important in the concession.

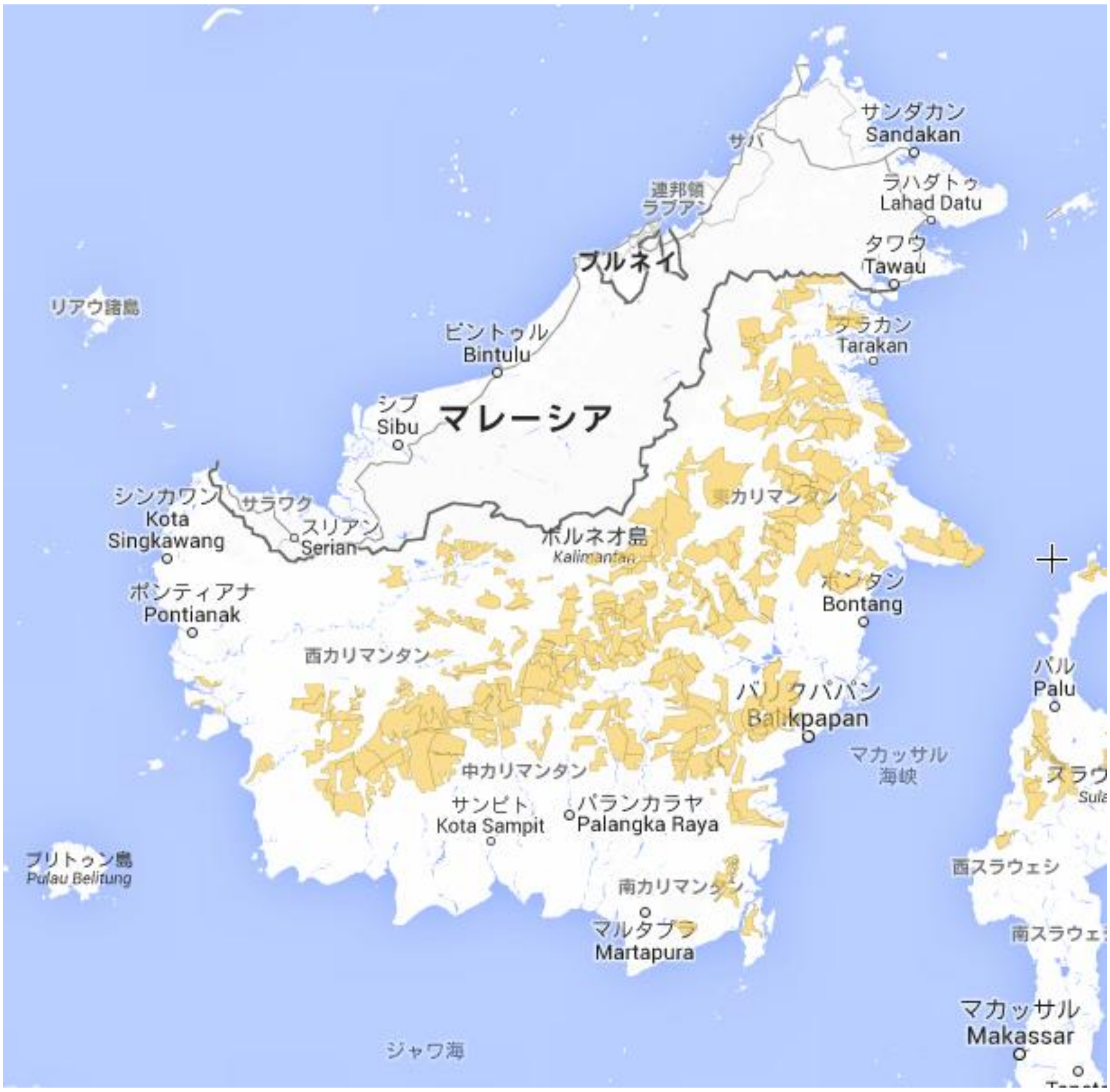

Fig. 1-1 Managed forests in the Indonesian Borneo (Global Forest Watch 2014)

Yellow indicates forests designated as timber production by logging company.

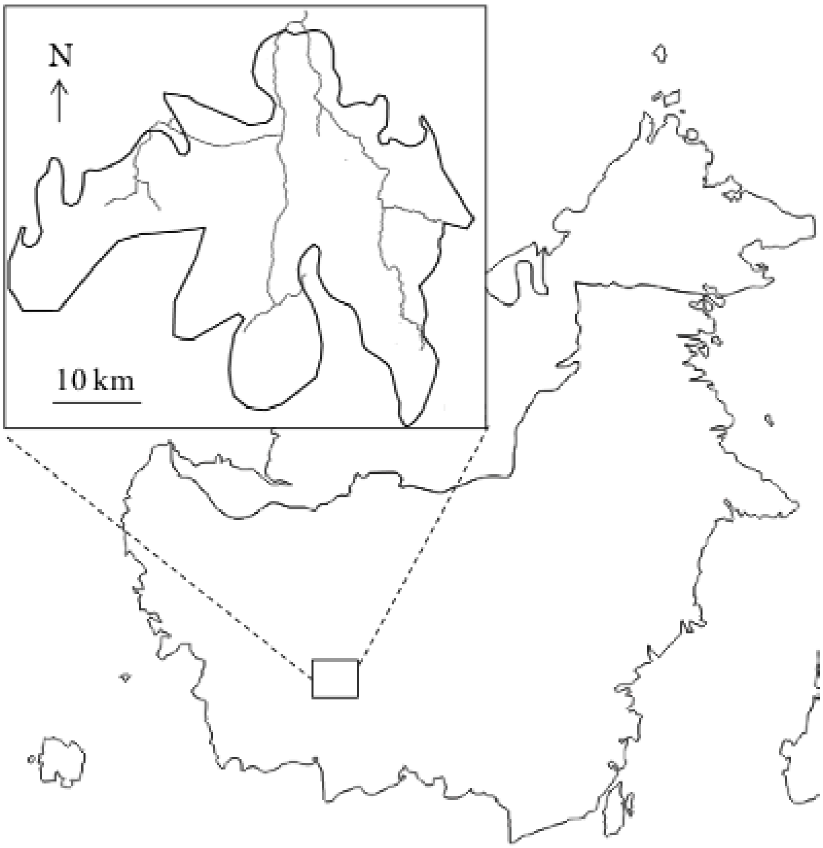

Fig. 1-2. Location of the study site

Chapter 2 Evaluation of the production sustainability of line planting system from the comparison of 10-years logged-over dynamics under different logging systems

INTRODUCTION

Unnecessarily destructive logging of the lowland dipterocarp forests of Southeast Asia has resulted in large expanses of degraded forests with low stocking of commercial timber trees, especially species of *Shorea* with "light red meranti" wood (Whitmore, 1990; Sist et al., 1998; Slik et al., 2003; Ng, 2009). To avoid further degradation, the application of RIL has been widely advocated (Pinard & Putz 1996; Bertault & Sist 1997; Lagan et al. 2007; Medjibe et al. 2011; Putz et al. 2008; Putz et al. 2012; Imai et al. 2014).

To further enhance stocking, enrichment line planting (LP) of seedlings of commercial species along cleared lines is also sometimes recommended (Weinland 1998, Schulze 2008, Edwards et al. 2009, Kettle 2010); LP is promoted by the Indonesian Ministry of Forestry (MoF) as Tebang Pilih Tanam Jalur (TPTJ) or selective logging and line planting system (Sève 1999; Chandrasekharan 2005).

The commercially important *Shorea* species that are traded as red or yellow meranti timber typically are often used in TPTJ (e.g., *S. leprosula* and *S. johorensis*). In the planting line, seedlings of meranti trees are planted along strips opened in selectively logged forest. The strips are opened to enhance the light condition of planted seedlings because of their light-demanding characteristics (Tuomela et al., 1996; Clearwater et al. 1999; Philips et al., 2002). Liberation thinning is sometimes used to improve the tree growth (Ådjer et al. 1995; Kammesheidt et al. 2003; Romell et al. 2008). Less common than these canopy-focused treatments is slashing of understory vegetation other than natural regeneration of commercial timber trees (Ådjers et al. 1995; Schulze 2008; Sovu et al. 2010).

Success with enrichment planting at the operational level in tropical forests has varied tremendously. Many of the failures can be attributed to the competition with other plants, particularly shading and suppression by lianas and other trees (Ǻdjers et al., 1995; Montagnini et al., 1997; Ashton et al., 2001; Matsune et al., 2006; Sovu et al. 2010). For adequate evaluation of the impacts of logging and other silvicultural treatments, such as line planting and understory slashing (LP/S), long-term monitoring of the growth and survival of planted trees and the residual future crop trees is necessary.

Here we evaluate the impacts of conventional logging (CL), reduced impact logging (RIL), and combination of RIL and line planting and slashing (LP/S) on the stocking and growth of commercial timber trees by comparison of 10-year post-logging dynamics in a lowland dipterocarp forest in Kalimantan, Indonesia. We assessed the effectiveness of RIL for mitigating logging impacts and of line planting with post-logging understory slashing for regeneration of commercial timber species

MATERIAL AND METHODS

Study area

In the study site, the monitoring plots were set in three management blocks different treatments applied (Fig. 2-1). Indonesian forestry regulation often changes (Ruslandi et al. 2014), but over the course of this study SBK worked towards a 25-year harvest cycle with focus on species of Dipterocarpaceae (e.g., *Shorea leprosula, and S. johorensis*) but also other commercial species including other dipterocarps (*Shorea* spp., *Hopea* spp., *Dipterocarpus* spp. and *Vatica* spp.). Some non-dipterocarps tree species [e.g. *Litsea firma* (Lauraceae), *Koompassia malaccensis* (Fabaceae), *Cratoxylon sumatranum* (Guttiferae)] were also harvested but 50-60 % of timber volumes harvested were from light-demanding *Shorea* species.

Experimental treatments

Three 1 ha monitoring plots were established in each of three logging compartments, one of which was subjected to conventional logging (CL) and two were logged with RIL techniques. In one of the RIL compartments, nursery-grown *Shorea johorensis* seedlings were line planted and all lianas, shrubs, ferns, and other large herbaceous plants, and pioneer tree seedlings were slashed every year after line planting (LP/S). The 100 ha CL site was logged in 1994, with a mean logging intensity of 10.4 trees/ha > 50 cm dbh and a harvest volume of 45.6 m^3/ha. The 72 ha RIL and 119 ha RIL+LP/S sites were logged in 2000 at mean logging intensities of trees >40 cm dbh of 9.1 and 9.3 trees/ha (44.1 and 45.5 m^3/ha), respectively. RIL was conducted by supervised workers that used skid trails that were planned on the basis of a preliminary inventory. Directional felling and pre-felling cutting of lianas were also used to minimize stand damage.

In the RIL+LP/S site, *S. johorensis* seedlings were planted at 5 m intervals along parallel 3-m-wide clear cut strips oriented north to south at 25-m intervals within six months following logging. The planted seedlings were grown from seed in a shaded nursery for 8-10 months. All plants rooted in the 3 m-wide strips were cut or logged, except for commercial timber species; trees with crowns overtopping the planting lines but rooted outside of the 3 m strip were left untouched. Five planting lines were cut in the three 100 × 100-m monitoring plots at the RIL+LP/S sites (Fig. 2-2). Initially, 103, 98, and 105 seedlings were included in the three 1 ha monitoring plots. *S. johorensis* is a moderately light-demanding species that were considered to be suitable for LP by previous investigators (Ådjers et al., 1995; Matsune et al., 2006; Phillips et al., 2002). The mean basal diameter of *S.johorensis* seedlings at the time of planting was 0.35 ± 0.1 cm.

In addition to LP, the entire plots were subjected to an annual slashing treatment for the duration of the 10-year monitoring period. In this treatment, pioneer tree seedlings and other understory vegetation were cut with machetes. The slashing treatment in the RIL+LP/S plots is unusual but was carried out to test the regeneration under intensive management. In actual management in the concession, the slashing was tended only in 3-m wide strip cutting lines for 3 years after planting annually.

Monitoring of forest structure and seedling recruitment

The first measurements were made 3-6 months after logging in the CL plots (1994) and RIL and RIL+LP/S plots (2000); the second measurement was conducted 1 year later with subsequent measurements made at 2 year intervals (1996-2004 in the CL plots and 2002-2010 in the RIL and RIL+LP/S plots). During each monitoring episode, the girths of all trees ≥ 10 cm dbh were measured at the position of a stripe painted at breast height (1.4 m) or above the buttress and newly recruited trees (i.e., trees reaching 10 cm dbh) were marked and measured (hereafter "pole recruitment"). Post-logging dynamics by trees ≥ 10 cm dbh under different treatments were monitored for 10 years.

Data analysis

We distinguished among the following six types of trees according to the commercial value and ecological function (Philips et al., 2002). The dipterocarps was separated into three subgroups: commercially important light-demanding *Shorea* species traded as meranti i.e., (Meranti), other commercial other dipterocarps (Not meranti), and non-commercial dipterocarps (Other dips). In the monitoring plots, *S. leprosula* and *S. johorensis* were recorded as meranti, other *Shorea* species with less light demanding characteristic were recorded and included in not meranti groups.

Pioneer species were *Macaranga* species and *Anthocephalus chinensis* (Pioneer). For others, tree species were separated into two subgroups, commercial (Other commercial) and non-commercial species (Other) other than dipterocarps and pioneers. For the six species groups, the post-logging pole recruitment (reached to 10 cm dbh) dynamics, stand growth by tree density and cumulative basal area were recorded.

Mortality rates were calculated for trees present at the first census as below (Sheil et al. 1995)

$$m = 1 - (1 - (n_0 - n_1) / n_0)\ 1 / y,$$

where m is the annual mortality rate between the two consecutive censuses, n is the population of trees recorded at the beginning and end of a given two census, y is the years between the two censuses.

Relative growth rates (RGRs) were calculated according to Hunt (1990)

$$\mathrm{RGR} = [\ln(d_0) - \ln(d_1)] / y,$$

where RGR is the relative growth rate per year, d_0 and d_1 are the dbh measured at two consecutive censuses, and y is the number of years between the twomeasurements.

To evaluate the impact of different treatments, the mortality rates and RGRs were calculated for trees ≥ 10 cm dbh present during the first census after logging (i.e., new recruits were not included).
Although the three 1 ha plots in each treatment area are technically "pseudo-replicates" (Hurlbert 1984), we compared mortality rates and growth rates among the three treatments with a one-way ANOVA when the normality assumption was met or the nonparametric Kruskal–Wallis test otherwise. Turkey's test or the nonparametric Steel–Dwass test was used for post-hoc multiple comparisons. A p-value <0.05 was considered to be significant.

RESULT

Changes in stand conditions and species composition

Tree densities and cumulative basal areas of trees ≥ 10 cm dbh trees increased in all three treatments (Table 2-1). Both tree density and basal area were lowest in the RIL+LP/S plots and highest in the CL plots soon after treatment. The mean post-logging cumulative basal area in the CL plots was greater than in the other two treatments. After 10 years, stocking was marginally higher in the RIL+LP/S plots, with no statistical difference among the three treatments. Although the planted trees contributed to the stocking of desirable *Shorea* species, stand stocks were still lower in all three treatments than in the primary forest in the concession (536 trees/ha and 32.1 m^2/ha).

Plots subjected to the three types of treatments differed in species group composition 10 years after logging. At the CL site, pioneer species increased from 2.7 ± 2.3 trees/ha to 41.7 ± 14 trees/ha 10 years later. At the end of the 10-year monitoring period, the density of pioneers at the CL site was statistically higher than in the RIL+LP/S site, but did not differ from the RIL site.

At the RIL site, pioneer trees were most abundant in the year after logging (18 ± 20.3 trees/ha) but varied greatly (0, 14 and 40 per plot). Natural disturbance prior to logging apparently explains this high initial pioneer density at the RIL plot. At 10 years after logging, unlike in the CL site, pioneer tree density at the RIL site decreased to 16 ± 9.5 trees/ha and meranti group trees increased from 6.3 ± 2.1 tees/ha to 12.7 ± 8 trees/ha. The greatest increase in natural (i.e., not planted) meranti tree density was observed at the RIL+LP/S site over the 10 years. It increased from 9.7 ± 8.1 to 54.7 ± 24.8 trees/ha excluding the planted trees. Observed increases in the density of not meranti and commercial group did not differ among the three treatments.

Mortality of residual trees

The temporal patterns of the mortality rate differed at the three sites (Table 2-2). The impact of logging was obvious at the CL site where the mortality rate in the initial monitoring period (1994 - 1995) exceeded 3%. The mortality rate then decreased steadily over the subsequent 9 years. In the RIL and RIL+LP/S plots, mortality was low for the first 4 years, increased 4-6 years after treatment, and then decreased again. Over the entire 10-year monitoring period there was no difference among the three treatments in average mortality rates.

Pole recruitment

The mean cumulative pole recruitment of trees (number of trees that reached 10 cm dbh in each monitoring episode) for 10 years at the CL, RIL, and RIL+LP/S plots were 178.3 ± 17.7, 117.7 ± 38.6, and 159.7 ± 33.1 trees/ha, respectively. The Steel-Dwass test indicated no difference among the three treatments (Table 2-3). The planted trees at RIL+LP/S plots were excluded from the result. As shown in species composition change, the recruitment dynamics of meranti and pioneer group differed among three treatments. More pioneer recruitment was observed in the CL plots (62 ± 18.4 trees/ha) than in the other two treatments. Over the 10-year observation period, peaks of pioneer recruitment in the CL plots were observed 2–4 and 6–8 years periods after logging. Pioneer recruitment in the RIL and RIL+LP/S plots were quite low, 10.7 ± 4 and 2.7 ± 2.1 trees/ha, respectively. In contrast, meranti species recruited poorly at the CL plots, where only 4.7 ± 4.6 trees/ha recruited into the 10 cm dbh class over the 10 years. Meranti recruitment was also not abundant in the RIL plots, only 7.3 ± 5.1 trees/ha recruited over 10 years. The most abundant natural recruitment of meranti was observed in RIL+LP/S plots. The cumulative recruitment of meranti trees was 46 ± 29.5 trees/ha. For 10 years, most abundant recruitments were found during the period 6 - 8 years after logging at RIL and RIL+LP/S plots (3.7 ± 1.2 and 24.3 ± 17.4 trees/ha, respectively, 2-3). In the RIL+LP/S treatments, the density of natural recruitment into the 10 cm dbh class varied widely among the three plots with cumulative numbers of recruited meranti trees for 10 years of 31, 27, and 80 trees/ha.

The impacts of logging on residual tree growth

The lowest mean RGR of residual trees over the 10 years was found at the CL plots (Fig. 2-3). The growth was better in the RIL plots, and the difference was significant at 1 year after logging. In the RIL+LP/S plots, RGRs were higher than in the RIL plots. Over the 10 years, residual tree growth was generally lowest in the CL plots and highest at the RIL+LP/S plots However, tree growth rates decreased during the period 2–4 years after logging at all sites. Comparing the size classes (Fig. 2-4), logging effects on RGR were greater on smaller trees (<30 cm dbh). The RGRs were higher among smaller trees compared to larger trees.

Survival and growth of planted *S. johorensis*

In the RIL+LP/S plots, the survival rate of planted trees over the first 10 years was 78.2 ± 6.7%. The average dbhs in the three plots were 15.7 ± 5.5, 14.8 ± 3.6, and 15.7 ± 4.6 cm but individual tree sizes varied widely (5.1- 30.8 cm dbh) among all 214 trees 10 years after planting. Only two trees reached to 30 cm dbh.

Size distribution of meranti group trees

10 years after logging, the densities of harvestable commercial dipterocarps (i.e., trees > 40 cm dbh) did not change in all three treatments, 5 ± 4.6, 1.7 ± 1.2 and 2.3 ± 0.6 trees/ha in CL, RIL and RIL+LP/S site, respectively (Table 2-4, Fig. 2-5). These numbers are less than the number removed at the initial harvest (9–10 trees/ha). The abundance of potential crop trees (10 - 40 cm dbh) of meranti trees in the CL plots increased only from 11.3 ± 6.1 to 13.7 ± 2.5 trees/ha. In contrast, potential crop trees increased from 4.7 ± 2.5 to 11 ±

7 trees/ha in the RIL plots. The highest number of potential crop trees was found in the RIL+LP/S plots where their density increased from 8 ± 6.1 to 52.3 ± 25 trees/ha. The planted *S. johorensis* in the RIL+LP/S plots further increased the density of meranti trees in the logged forest. In each RIL+LP/S plots, 75, 84 and 80 planted trees (66, 77 and 71 trees > 10 cm dbh) survived. Including the planted trees, the density of potential crop tree increased to 106.2 ± 25.9 trees/ha in the10 years after treatment.

The abundance of natural recruits varied widely among the three plots (31, 27 and 80 trees/ha) within the RIL+LP/S site, whereas the among-plot variation of abundance was smaller for planted trees than for natural recruits.

DISCUSSION

The effects of RIL on post-logging stand dynamics

Although the harvested volumes from the CL, RIL, and RIL+LP/S treatment plots were moderate (Sist and Nguyen-Thé 2002), the densities and basal areas of trees ≥10 cm dbh were still low 10 years after treatment (Table 2-1).

We noted differences in the species group composition and pole recruitment rates among the three treatments 10 years after the onset of observations. The differences are significant for meranti species and pioneer species, both light-demanding groups. After CL, pioneer tree densities increased dramatically 1–2 years after logging (Table 2-3). In the RIL plots, in contrast, pioneer recruitment was low, indicating that logging impacts were diminished as intended and reported in previous studies (Pereira et al. 2002; Lagan et al., 2007; Imai et al., 2012). Pioneer recruitment was further suppressed by intensive annual slashing in the RIL+LP/S plots.

Meranti tree recruitment into the ≥10 cm dbh class peaked 6–8 years after logging in the RIL and RIL+LP/S plots. This recruitment peak was not observed in the CL plots presumably due to canopy closure by pioneer species (Slik and Eichhorn, 2003; Romell *et al.*, 2008).

During the first year after felling, annual mortality rates exceeded 3% in the CL plots but were lower in the RIL and RIL+LP/S plots, which indicates that RIL achieved its goal of reducing damage to residual trees. Surprisingly, mortality rates over the 10 years observation period did not differ among treatments.

Growth rates of residual trees were higher in the RIL+LP/S plots than in the other treatments. Rates were lowest at the CL treatment site for most of the 10-year monitoring period. In the RIL and RIL+LP/S plots, residual tree growth was promoted by the reduction of logging damage to trees (Fredericksen and Putz, 2003). This effect was particularly marked in the RIL+LP/S treatment site, which was subjected to strip-cutting and slashing. Canopy opening and removing competitors apparently promoted tree growth. This positive effect on tree growth was strong in small trees. The canopy layer of lowland dipterocarp forest has a multilayered structure (Romell and Karlsson, 2009), with smaller trees located in the lower canopy layer. Harvesting of trees from the upper layer trees changes light conditions and stimulates tree growth (Peña-Claros *et al.*, 2008).

In the RIL and RIL+LP/S plots, growth and mortality rates of residual trees during the period 2–4 years after logging were relatively low, but increased in the period 4–6 years after logging. This change in growth rates may be explained by shifts in resource allocation away from branch extension to trunk diameter growth. Trees expand their branches initially to better intercept sunlight and to compete with neighboring trees for incoming radiation (Inada, unpublished observation). This investment in branch expansion can affect tree stem growth (Wadsworth and Zweede, 2006), and may have promoted high growth rates in superior competitors at the expense of individuals that died in the period 4–6 years after logging. Conventional unplanned logging killed and injured trees that then died, whereas after RIL, mortality seemed more related to density effects and competition given that mortality rates over the 10-year observation period did not change. These findings emphasize the importance of long-term observations on the effectiveness of RIL methods.

Regeneration of desirable *Shorea* spp. under intensive management

Inhibition of meranti regeneration by pioneers was not apparent at the RIL plots, but was obvious after CL (Table 2-3). Nevertheless, the density and pole recruitment of meranti trees were not higher at the RIL treatment site. In contrast, natural regeneration that reached 10 cm dbh after logging was abundant in the RIL+LP/S plots; recruits of meranti trees (*S. leprosula* and *S. johorensis*) to pole size were particularly abundant. The light-demanding seedlings of *Shorea* spp. recruit best under a partially open canopy (Tuomela *et al.*, 1996; Tennakoon *et al.*, 2005). The effects of RIL for the regeneration of light demanding *Shorea* species are controversial (Fredericksen and Putz. 2003; Sist and Brown, 2004). Substantial canopy opening is required for the growth and it might be suppressed under RIL. From the hemispherical photography, the effect of strip cutting on the forest floor light condition was suggested (Inada et al. 2013).

For planted *S. johorensis*, enhancement of light condition by liberation from neighboring trees and removing competitor e.g. shrubs and lianas, were effective for their growth (Ådjers et al. 1995). The better light conditions created by RIL plus strip-cutting were likely effective in promoting meranti recruitment. Removal of competitors by slashing was also likely to have enhanced natural recruitment and the growth of planted *S. johorensis* (Wadsworth and Zweede, 2006; Schulze, 2008; Keefe et al., 2009; Pamoengkas et al. 2014). Overall, many desirable *Shorea* seedlings recruited under intensive management by strip-cutting and slashing, but we noted large differences in the number of recruits among the three RIL+LP/S plots, suggesting that regeneration of desirable species may have been dependent on the abundance of mother trees and the size of the seedling bank at the time of treatment (Sovu *et al.*, 2010).

Effectiveness of line planting for sustainable management

Planted *Shorea* trees survived well and grew rapidly over 10 years of observations of the RIL+LP/S plots. Mortality rates are generally low among faster-growing individuals located in favorable micro-sites (Ong and Kleine, 1995). Planted *S. johorensis* had marked higher survival rates compared to those previously reported for *S. johorensis* wildings transplanted post-logging (55–72.5% 2 years after planting, Ǻdjers et al., 1995; 38–64.6% for 3 years after planting, Matsune et al. 2006). Although the canopy openness varied gradually along the planting lines (Inada et al. 2013), they have wide adaptability to different light condition (Brown 1996; Clearwater et al. 1999). And removing competitor by slashing resulted the high survival rate for 10 years. Line-planted trees that were growing well were likely to survive and contribute to the next harvest that is planned to take place 15 years after the last measurement reported in this study. Total densities and basal areas of trees > 10 cm DBH of planted trees and unplanted trees in the RIL+LP/S plots reached 432 ± 35/ha and 23.5 ± 2.5 m^2/ha, respectively, after 10 years (Table 2-1). Thus, we conclude that the line-planting treatment was effective in promoting commercial *Shorea* stocking.

Prospects for sustainable timber yield under the three management options

Compared to the primary forests in the region (Manokaran and Kochummen, 1987; Ong and Kleine, 1995; Bischoff *et al.*, 2005), the three sites at our study had higher RGRs but similar mortality rates during the period 8–10 years after logging. Residual trees apparently were able to recover from logging damage. Forest dynamics after large disturbances influence seedling recruitment (Denslow, 1987; Shugart, 1984), and our monitoring of pole recruitment dynamics over 10 years after logging produced information of relevance to forest managers. Reduced-impact logging stimulated pole size (> 10 cm dbh) recruitment of meranti species peaking 6–8 years after logging. Subsequently, the increased light effect that had stimulated recruitment in the aftermath of logging gradually diminished and then disappeared. The recruitment of commercially desirable *Shorea* species is sometimes poor in primary forest (Manokaran and Kochummen, 1987; Ong and Kleine, 1995), and natural recruitment without augmentation, e.g. slashing or line planting conducted in RIL+LP/S plots would not permit the development of sustainable timber yields within the 25-year logging cycle planned for the concession in which we worked. Our 10 years of monitoring suggests that setting the logging cycle to a longer time frame will be necessary, as recommended by other studies (Huth and Ditzer, 2001; Sist *et al.*, 2003; Sist and Ferreira, 2007). In lowland dipterocarp stands, un-tended natural regeneration after even RIL will likely not be adequate for sustainable timber yields with cutting cycles of <40-50 years. Based on the abundant natural regeneration of commercial species in the RIL+LP/S plots, release treatments seem sufficient to sustain timber yield. The enrichment line planting indicated the efficiency for reintroducing the desirable species into logged over forest as suggested in previous studies (Ådjers et al. 1995; Montagnini et al. 1997; Ashton et al. 2001; Paquette et al. 2006; Sovu et al. 2010). However, the high cost of establishment and tending will reduce the income (Lamb, 1969; Hartshorn, 1995; Appanah and Weinland, 1996; Putz 2004; Ruslandi et al., 2014), and the financial incentive might covert to the forest dominated by a few fast-growing desirable trees like plantation (Schulze 2008; Putz & Redford 2009). However, the natural regeneration of desirable species was insufficient without any post-logging silvicultural treatment. The under slashing and line planting were practical. These two treatments differed in the dependence on the regeneration ability in logged over forest. The regeneration of desirable species would be promoted by tending if there is abundant residual mother trees and seedling bank, however, if not, enrichment planting was recommended (Schwartz et al.

2013). As post-logging management, slashing treatment would be effective and lower cost compared to line planting. The intrusive and expensive treatment of LP does not seem necessary but might still be preferred if extremely high yields of *Shorea* spp. are desirable. In the RIL methods, preliminary inventory of harvestable trees and potential crop trees is conducted. The inventory census would be informative to make a decision to install the line planting.

Feasibility of the line planting system for the sustainable management

Poor growth, low recruitment of commercial timber species, and pioneer invasion in the CL plots demonstrated considerable degradation of the forest ecosystem and little potential for sustainable timber yields. In contrast, RIL effectively reduced damage from selective logging but 10 years of subsequent monitoring revealed that this treatment alone may not be sufficient to sustain timber yields unless the cutting cycle is extended from the current 25 years. In contrast RIL plus post-logging silvicultural treatments did successfully regenerate the commercial timber tree species. The enhancement of light conditions by opening strips in the canopy and slashing of non-commercial understory species and lianas served to increase both the stock and growth of commercial species. The line planting of *S. johorensis* seedlings and subsequent tending further increased stocking levels to very high levels. However from the cost perspective, promoting natural regeneration by slashing was preferred to line planting.

Overall, our analysis of post-logging dynamics over 10 years suggests that RIL combined with stand-tending operations to promote natural regeneration seems like a cost-effective way to sustain yields. Although enrichment line planting was effective to reintroduce the meranti trees in degraded forest, it should be installed partially to avoid the high cost and unnecessary simplification of stand structure and composition.

Table 2-1 Stand parameters for trees ≥10 cm dbh 3-6 months after logging and 10 years later at sites subjected to conventional logging (CL), reduced-impact logging (RIL), or RIL followed by line planting and annual understory slashing (RIL+LP/S); values are means ± SD in 1 ha plots (n = 3 per treatment). For RIL+LP/S, planted trees were not included. Mearanti, commercailly important light demanding *Shorea leprosula* and *S. johorensis*; Not meranti, commercial dipterocarps other than meranti species; Other dips, other non-commercial dipterocaros; Commercial, commercial species other than dipterocarps; Pioneer, principally *Macaranga* spp. and *Anthocephalus chinensis*; Other, all the non-commercial species other than dipterocarps and pioneers.

Treatment	Species group	Mean tree density (/ha)		Mean basal area (m^2/ha)	
		Year of logging	10 years later	Year of logging	10 years later
CL	Meranti	17 ± 11.8	18.7 ± 6.4	2.9 ± 1.8	2.2 ± 1.6
	Not meranti	27.3 ± 24.8	30.3 ± 25.7	1.7 ± 1.0	2.1 ± 1.3
	Other dips	15.3 ± 3.5	16 ± 5.2	2.5 ± 0.8	2.8 ± 0.8
	Commercial	52.3 ± 3.8	61.7 ± 5.9	3.2 ± 0	3.8 ± 0.9
	Pioneer	2.7 ± 2.3	41.7 ± 14	0	1.2 ± 0.4
	Other	215 ± 56.7	248 ± 29.8	14.7 ± 6.3	14.8 ± 3.5
	Total	329.7 ± 78.1	416.7 ± 74	25.1 ± 3.1	26.9 ± 2.8
RIL	Meranti	6.3 ± 2.1	12.7 ± 8	1.3 ± 0.7	1.3 ± 0.7
	Not meranti	39.3 ± 21.2	46.7 ± 25.4	4.5 ± 3.6	5.1 ± 3.2
	Other dips	11.7 ± 3.2	13.3 ± 6.7	0.7 ± 0.6	0.6 ± 0.2
	Commercial	65.3 ± 12.7	78 ± 10.5	2.8 ± 0.4	3.8 ± 0.2
	Pioneer	18 ± 20.3	16 ± 9.5	0.3 ± 0.3	0.8 ± 0.6
	Other	153.7 ± 16.6	187.7 ± 24.8	8.3 ± 2.6	11.2 ± 2.7
	Total	294.3 ± 16.3	354.3 ± 52.5	18 ± 0.1	22.8 ± 0.3
RIL+LP/S	Meranti	9.7 ± 8.1	54.7 ± 24.8	0.9 ± 0.8	1.9 ± 0.2
	Not meranti	54.7 ± 14.3	67.3 ± 8.1	5.7 ± 3.3	6.8 ± 2.8
	Other dips	5.3 ± 1.5	10.3 ± 5.7	0.5 ± 0.3	0.9 ± 0.4
	Commercial	71.7 ± 5.9	80.3 ± 6	3.2 ± 0.4	4.3 ± 0.5
	Pioneer	11.7 ± 12.4	10.3 ± 9.3	0.2 ± 0.2	0.6 ± 0.5
	Other	1.8 ± 7.9	137.7 ± 14.7	5.6 ± 0.2	7.6 ± 0.9
	Total	258 ± 1	360.7 ± 36.5	16 ± 3	22 ± 2.4
	(including planted trees)		432 ± 35		23.5 ± 2.5

Table 2-2 Mean annual mortality rate (%) for all residual trees ≥10 cm DBH during each post-logging monitoring period by treatment, conventional logging (CL), reduced-impact logging (RIL), or RIL followed by line planting and understory slashing (RIL+LP/S). Rates are means ± SD in 1 ha plots (n = 3 per treatment).

Treatment	Monitoring period (year)						
	0-1	1-2	2-4	4-6	6-8	8-10	Average
CL	3.7 ± 1.2	2.9 ± 3.5	2.6 ± 0.7	1.5 ± 0.9	1.3 ± 1.1	1.5 ± 0.8	2.1 ± 0.3
RIL	1.8 ± 0.9	2.1 ± 1	0.7 ± 0.3	3.4 ± 1	1.7 ± 0.7	1.2 ± 0.6	1.8 ± 0.1
RIL+LP/S	1.6 ± 0	2.9 ± 0.2	0.7 ± 0.5	4.4 ± 1.1	1.5 ± 1	1.5 ± 0.3	2.1 ± 0

Table 2-3 Pole-recruitment (number of trees attaining 10 cm dbh) during each post-logging monitoring period at sites subjected to three treatments, conventional logging (CL), reduced-impact logging (RIL), or RIL followed by line planting and understory slashing (RIL+LP/S) (values are mean recruit densities ± SD in 1 ha plots, n = 3 per treatment). Mearanti, light demanding *Shorea leprosula* and *S. johjorensis*; Not meranti, commercial dipterocarps other than meranti species; Other dips, other non-commercial dipterocaros; Commercial, commercial species other than dipterocarps; Pioneer, *Macaranga* genus species and *Anthocephalus chinensis*; Other, other non-commercail species other than dipterocarps and pioneers.

Treatment	Species group	Monitoring period (year)						Cumulative
		0-1	1-2	2-4	4-6	6-8	8-10	
CL	Meranti	0.7 ± 1.2	0.7 ± 1.2	0.3 ± 0.6	1 ± 1.7	0.7 ± 1.2	1.3 ± 1.2	4.7 ± 4.6
	Not meranti	1.7 ± 2.1	3 ± 3.5	0.3 ± 0.6	1.3 ± 1.2	0.7 ± 0.6	0.3 ± 0.6	7.3 ± 5.1
	Other dips	0	1 ± 1	0.3 ± 0.6	0	0.7 ± 0.6	0.3 ± 0.6	2.3 ± 1.5
	Commercial	2 ± 1	8 ± 5.3	2.7 ± 0.6	2.3 ± 1.2	2 ± 1	1.3 ± 1.5	18.3 ± 8.1
	Pioneer	0	19.7 ± 9.9	16 ± 6.6	0.7 ± 0.6	25.7 ± 14.4	0	62 ± 18.4
	Other	10.7 ± 8.6	34.3 ± 1.7	8.3 ± 2.1	3.3 ± 2.5	12.7 ± 6	14.3 ± 6.8	83.7 ± 27.2
	Total	15 ± 8.5	66.7 ± 10.3	28 ± 4.6	8.7 ± 0.6	42.3 ± 22.7	17.7 ± 9	178.3 ± 17.7
RIL	Meranti	0.3 ± 0.6	0	0.7 ± 1.2	1 ± 1	3.7 ± 1.2	1.7 ± 2.9	7.3 ± 5.1
	Not meranti	1.3 ± 1.5	1.7 ± 2.9	1.3 ± 0.6	3 ± 2.6	6 ± 6.6	1 ± 1	14.3 ± 12.7
	Other dips	1 ± 1.7	0	0.7 ± 0.6	0.3 ± 0.6	1.3 ± 1.5	1 ± 1	4.3 ± 3.8
	Commercial	3.7 ± 2.1	3.3 ± 0.6	4.7 ± 1.5	3.3 ± 2.0	7 ± 4.4	2 ± 1	24 ± 4.6
	Pioneer	1.3 ± 1.5	4.3 ± 3.1	4.3 ± 3.1	0	0.3 ± 0.6	0.3 ± 0.6	10.7 ± 4
	Other	11 ± 6.1	4.7 ± 1.5	4.3 ± 4.2	7 ± 1	25.7 ± 6.1	4.3 ± 1.5	57 ± 13.9
	Total	18.7 ± 8.1	14 ± 2.6	16 ± 9.2	14.7 ± 3.8	44 ± 16.4	10.3 ± 1.5	117.7 ± 38.6
RIL+LP/S	Meranti	0.7 ± 0.6	0.3 ± 0.6	0.7 ± 0.6	10.7 ± 5.5	24.3 ± 17.4	9.3 ± 7.6	46 ± 29.5
	Not meranti	1.7 ± 1.5	3.3 ± 1.5	4.7 ± 2.5	5.7 ± 102	12.3 ± 9.7	2 ± 1	29.7 ± 9.5
	Other dips	1 ± 1.7	0.3 ± 0.6	0.3 ± 0.6	0	2.7 ± 2.5	1 ± 1.7	5.3 ± 4.6
	Commercial	4.7 ± 2.3	2.4 ± 0.6	4 ± 1	3.7 ± 2.9	6 ± 3.6	1.3 ± 1.5	22.3 ± 6
	Pioneer	1.3 ± 0.6	0.7 ± 1.2	0.3 ± 0.6	0	0	0.3 ± 0.6	2.7 ± 2.1
	Other	12.3 ± 3.1	2.3 ± 1.5	4.7 ± 3.5	8 ± 4	23 ± 2.6	3.3 ± 2.1	53.7 ± 3.2
	Total	21.7 ± 1.5	9.7 ± 4.6	14.7 ± 5.5	28 ± 6.9	68.3 ± 27.2	17.3 ± 7.1	159.7 ± 33.1

Table 2-4 Number of naturally recruited (i.e., not planted) stems of meranti, commercial *Shorea* spp. (*S. leprosula* and *S. johorensis*) in three treatments immediately after logging operations (1994 in CL and 2000 in RIL and RIL+LP/S site) and 10 years later (2004 in CL and 2010 in RIL and RIL+LP/S site). Values are mean ± SD in 1 ha plots (n = 3 per treatment).

DBH class (cm)	Logging year			10 years after logging		
	CL	RIL	RIL+LP/S	CL	RIL	RIL+LP/S
10-20	6.3 ± 1.2	2.3 ± 1.5	5 ± 5.3	5.3 ± 3.2	7.3 ± 4.5	42 ± 22.5
20-30	2 ± 2.6	1.3 ± 1.5	2.7 ± 2.1	3.7 ± 1.2	1.3 ± 1.2	7.7 ± 3.5
30-40	3 ± 2.6	1 ± 1.7	0.3 ± 0.6	4.7 ± 2.5	2.3 ± 1.5	2.7 ± 0.6
40-	5.7 ± 5.7	1.7 ± 0.6	1.7 ± 2.1	5 ± 4.6	1.7 ± 1.2	2.3 ± 0.6

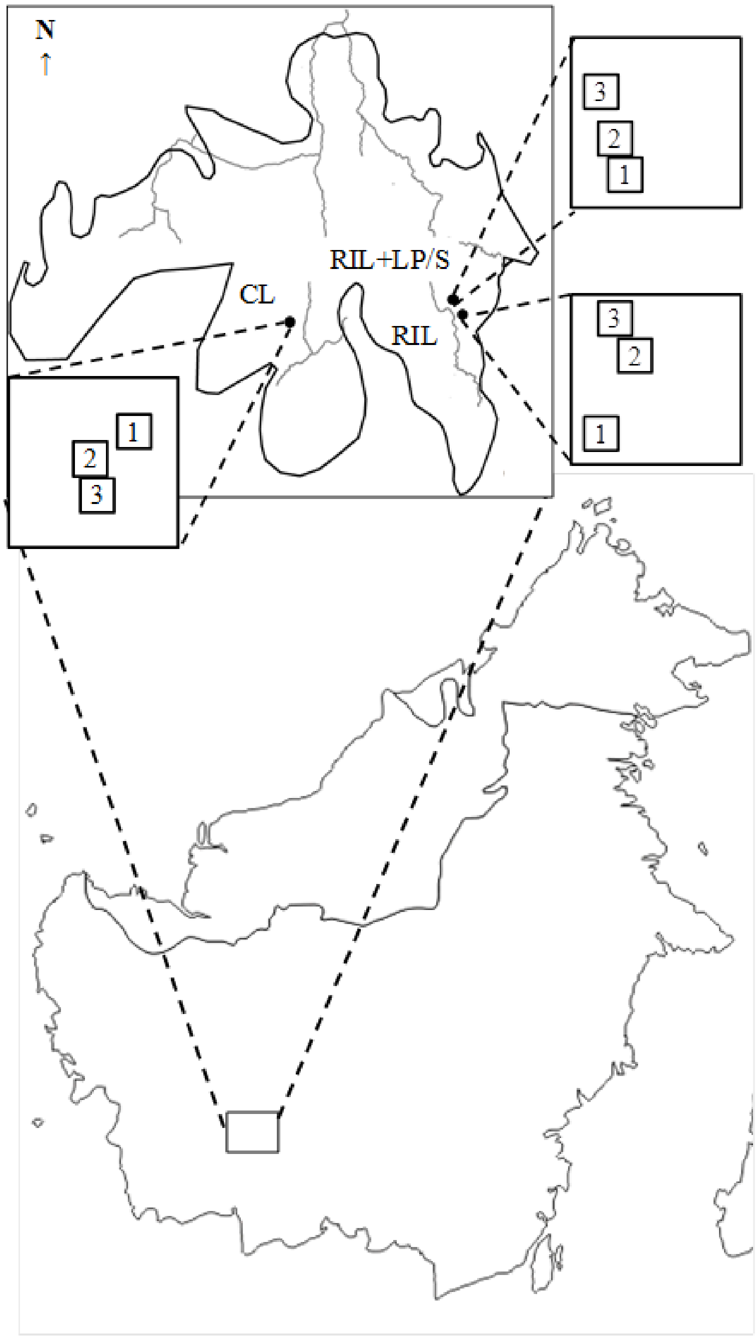

Fig. 2-1. Map of the concession area and the sites where this study was conducted.

In each site subjected to conventional logging (CL), reduced-impact logging (RIL), or RIL followed by line planting and understory slashing (RIL+LP/S), three 200 × 200 m quadrats were established in which there was a 100 ×100 m monitoring plot.

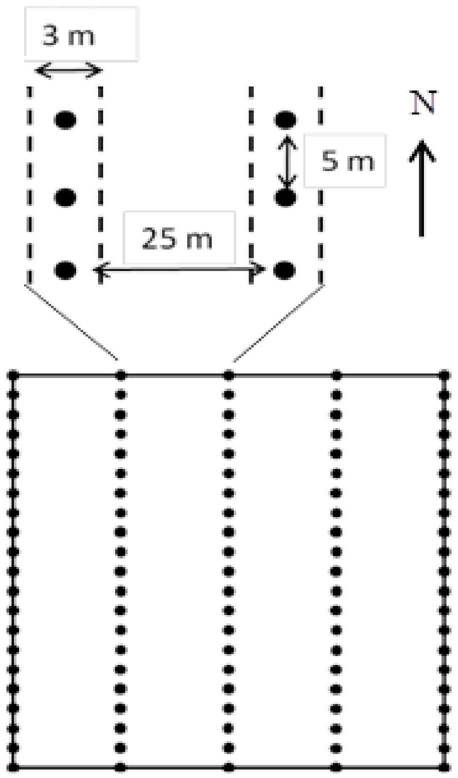

Fig. 2-2. Schematic of the line planting treatment and layout of the monitoring plots in the reduced impact logging+line planting (RIL+LP/S) treatment site. Strip-cutting of 3-m bands was performed along a north to south axis at 25-m spacing intervals. Seedlings were planted in a line with 5-m spacing intervals. In total, 105 seedlings were planted in this system. Filled circles represent planted trees. All lianas pioneer seedlings and understory vegetation were slashed every years after logging.

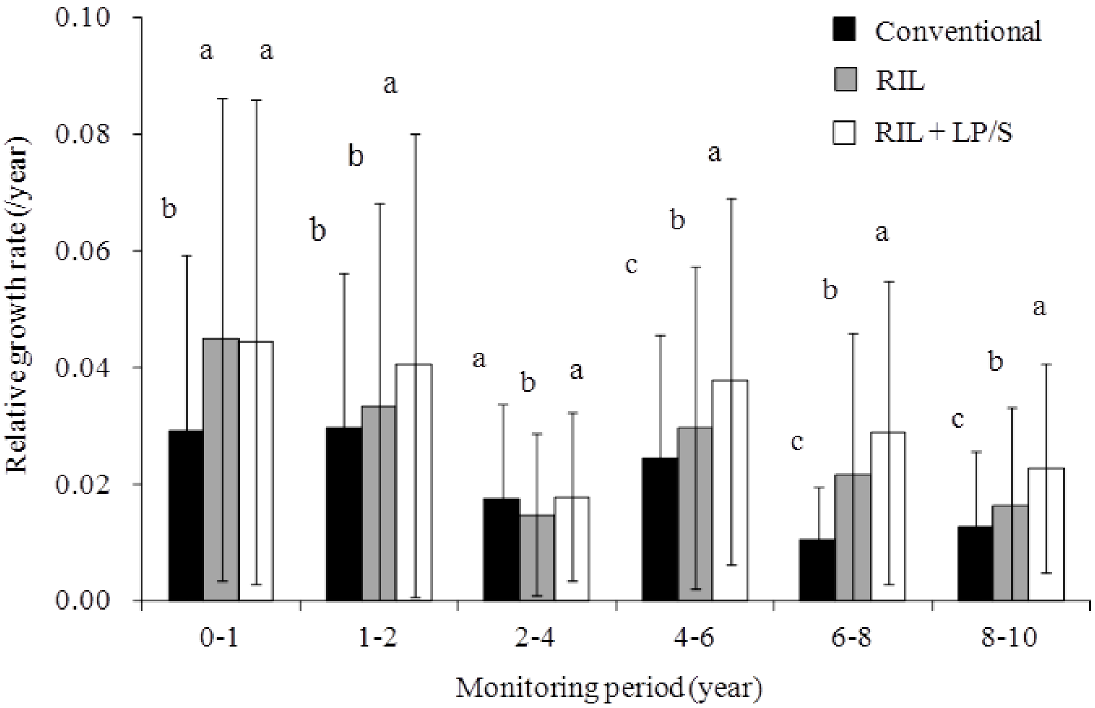

Fig. 2-3. Relative growth rates (RGRs for diameter at breast height, dbh) of residual trees ≥10 cm dbh during each monitoring period at sites subjected to three different treatments. Values are means ± SD. Different lowercase letters above the bars indicate significant differences (one-way analysis of variance followed by a multiple comparisons test, $p < 0.05$). RIL, reduced-impact logging; RIL+LP/S, line planting + annual slashing after RIL.

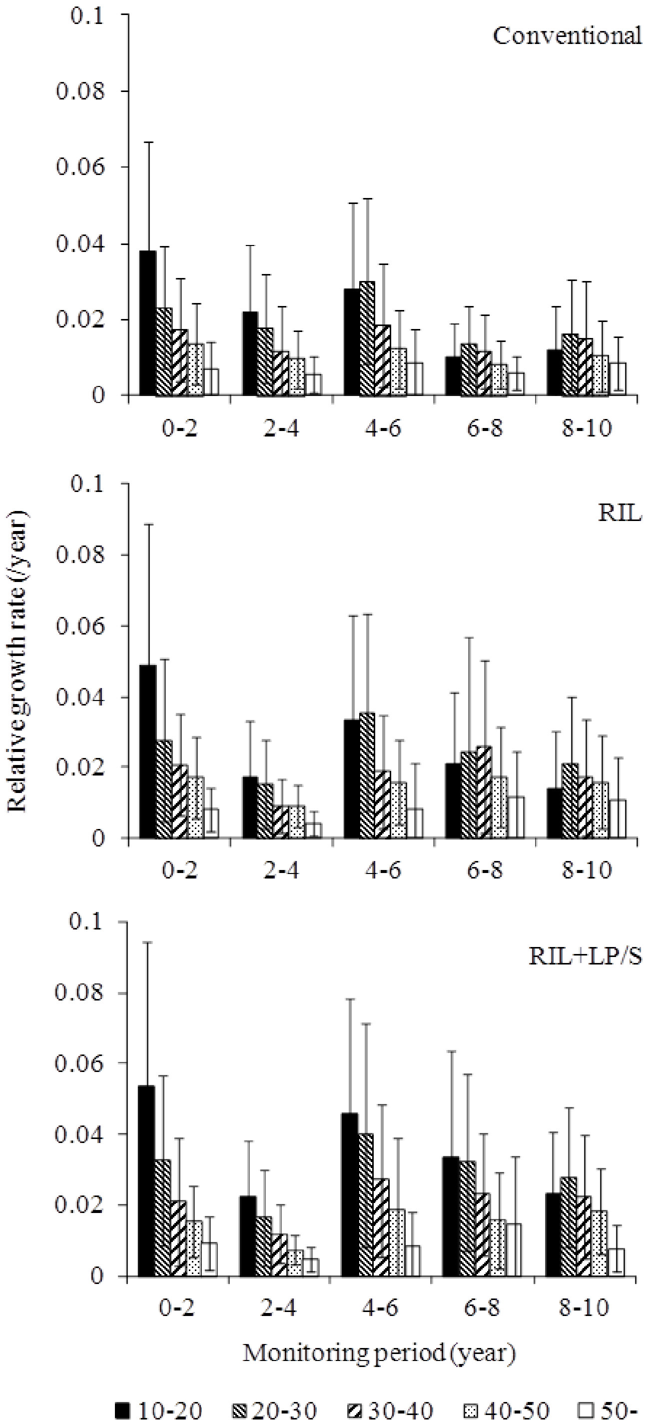

Fig. 2-4. Relative growth rates (RGRs for diameter at breast height, dbh) of residual trees (each ≥10 cm dbh) by size class at each treatment site. Bar shading indicates size classes, which are keyed beneath the lowermost horizontal axis. RIL, reduced-impact logging; RIL+LP/S, line planting + annual slashing after RIL.

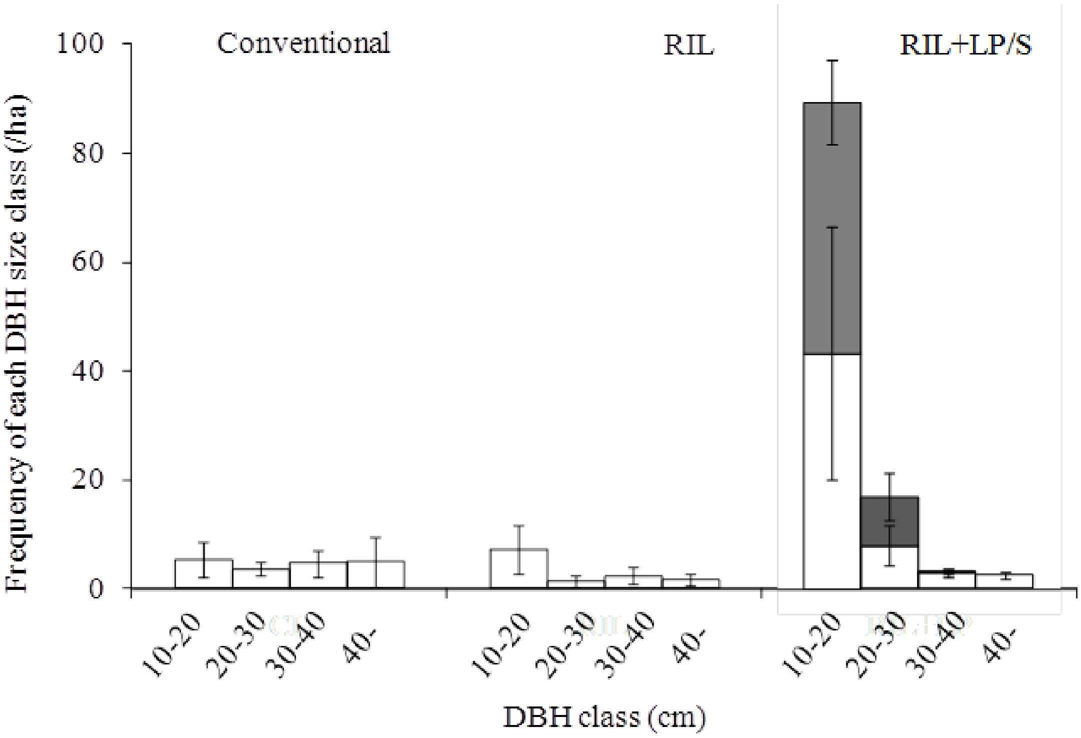

Fig. 2-5. Frequency distributions of diameter at breast height (dbh) for meranti trees in each of the three treatment sites 10 years after planting. Bar shading in the line planting + annual slashing after reduced-impact logging (RIL+LP/S) treatment site indicates the planted *Shorea johorensis*. Values are means ± SD ($n = 3$). RIL, reduced-impact logging.

Chapter 3 Effect of selective logging and line planting system on the forest understory condition

INTRODUCTION

Reduced impact logging (RIL) method was designed to reduce the damage to residual trees and suppress the pioneer invasion by mitigating canopy opening. However, the quantitative evaluation of the impact on light condition was scarce in lowland dipterocarp forest. In the line planting system used in Indonesia, to improve the light condition of planted light demanding *Shorea* seedlings, strip-cutting treatment was conducted, because planted *Shorea* species are light demanding members in dipterocarps (Mauricio, 1987, Ashton, 1998, Clearwater et al. 1999; Mori 2001). Light condition is an important factor influencing survival and growth for planted trees (Tuomela et al. 1996; Romell et al. 2008). However, the strip-cutting treament may induce the further disturbance to the logged-over forest after RIL, and the light condition in the strip cutting line has not been evaluated.

Canopy openness (CO) and net solar r
adiation on the forest floor depend on the spatial structure of canopy layers (Montgomery & Chazdon 2001; Silbernagel & Moeur 2001). In logged-over forests, strip cutting was applied creating a specific “linear” gap regime that may be different from typical logging gaps. The duration of exposure to direct sunlight may be different between gap created by extraction of trees and the linear gap created for the line planting even the CO of both gaps being the same. Such a different light condition created by the difference of logging systems may induce different dynamics.

This study aims to assessing the effects of RIL and strip cutting treatment on the light condition of forest floor. To achieve it, we conducted hemispherical canopy photography in primary forests and logged-over forests in which the two logging systems (RIL only or RIL and strip cutting) were applied, to assess the difference of the effects on light condition between those two logging systems. In addition, we took photographs along strip cutting lines to assess the effect of this treatment on the light conditions of planted trees.

MATERIAL AND METHODS

Study site and plot setting

Three sites were selected for hemispherical photography. First, a primary forest site was chosen as a control (PF site; 00°38'54"S, 112°13'04"E). To evaluate the effects of logging activities (i.e. logging gaps, skid trails and strip cutting), two photography sites were set in logged-over forests that were logged using different logging systems in 2011. One site was a logged-over forest that targeted trees were more than 50 cm diameter at breast height (DBH) using selective logging with RIL methods (S site; 00°51'16"S, 111°59'51"E). The other site was treated with 3-m-wide strip cutting after selective logging with RIL, targeting trees with DBH values greater than 40 cm (SL site; 00°51'26"S, 112°00'06"E). At SL, 3-m-wide strip cutting was conducted at 20–25-m intervals from north to south. In the strip cutting line, all of the trees excluding commercial species and understory plants were clearly removed at 6 months after logging. No canopy treatments such as girdling or pruning were performed. Some Shorea species would be planted at 2.5-m intervals along the lines. This study was conducted before the planting.

In each site, a monitoring plot was established and trees were monitored from Sep. to Nov. 2011. The monitoring plots established in the PF, S, and SL sites measured 4, 2.25, and 3 ha, respectively, and the basal areas of trees >10 cm were 32, 22.9, and 18.5 m2/ha, respectively. At each of the three sites, three 50 × 50-m plots were placed at random for hemispherical photography. Relative elevations in all plots were surveyed using a LaserAce Hypsometer (Measurement Devices, Ltd. York, U.K.). The difference in slope position in

50x50m plots was within about 20 meters except PF3 and S2 (Table 3-1). At the PF site, plots were chosen in stands with closed canopies. At both of the logged-over sites, trails from logging activities (skid trails and logging gaps) and strip cutting lines were mapped in all plots. Skid trails were approximately 3–4 m wide. Within a plot, 49 photography points were taken with a 5-m spacing. These 5-m grids were located in the interior of the plot, 10 m from the plot boundary, to avoid the inclusion of canopy of trees and logging effects located outside the plot. In addition, three strip cutting line transects were chosen near the plots at the SL site. In a strip cutting line, hemispherical photographs were taken with 5-m spacing over 100 m; 21 photographs were taken per line (Fig. 3-1). In total, nine plots and three line transects were established.

Hemispherical photography

Hemispherical canopy photography is widely used to assess light conditions (Chazdon and Field, 1987; Rich, 1989; Rich et al., 1993; Frazer et al., 2001). Hemispherical photographs were taken in October 2011, before planting, about half a year after logging. Photographs were taken on days with uniform overcast skies to avoid sun reflections on vegetation and direct sunshine. The photography equipment included a digital camera (Coolpix 8400; Nikon, Tokyo, Japan) with an attached fisheye converter FC-E9 0.2× lens (Nikon). The camera was mounted on a tripod, the lens was set at a height of 1.2 m and the camera was oriented so that the top of the photograph faced magnetic north. Photographs were taken according to the Open-sky Reference Method (ORM) that Tani et al. (2011) proposed. ISO sensitivity was set to 10,000. The aperture setting was selected automatically with a shutter speed of 1/500 s under open-sky conditions. Three photographs were taken at each photo point with shutter speeds of 1/125, 1/250, and 1/500 s. Among the three pictures that were taken in each subplot, one picture was selected by visual examination for image analysis.

Image analysis

Hemispherical photographs were analyzed using Gap Light Analyser (GLA) Ver. 2.02 (Frazer et al., 1999). This software has been used in several studies (Jarčuška, 2008). GLA changes photographs to binary images of 'sky' or 'not sky' based on thresholds that refer to an open-sky condition, according to ORM methods. CO was calculated in each of the three sites. The light condition is not determined solely from the CO; the width and direction of the canopy opening are also important. Then, we simulated the cumulative sun-fleck duration within 1 year at all three sites and strip cutting lines. The duration was simulated by assuming it was sunny every day at the measured latitude and longitude of each site. As a result, 147 image sets for each site and 63 image sets for cutting lines were analysed.

Data analysis

To evaluate the effects of logging and strip cutting treatment on canopy openness, the statistical differences in the mean CO among the three sites were assessed using the Kruskal–Wallis test to detect the difference in the distribution of CO between site S and SL. In addition, from the plot maps, we separated all the photo points into the elements disturbance, intact, skid trail, logging gap, and strip cutting line (SL sites only) and compared the CO among the elements using one-way analysis of variance (ANOVA). When the one-way ANOVA was significant, differences among the elements were determined using Tukey's test. The correlation between the CO value and simulated cumulative sun-fleck duration for 1 year was analyzed using Pearson's correlation coefficient analysis and single regression for each of the three sites. In addition, the slopes of the regression among three sites and strip cutting line were compared using analysis of covariance (ANCOVA). If the ANCOVA was significant, differences among three sites and strip cutting lines were estimated using Bonferroni's test to evaluate the effects of strip cutting treatment on light condition. The distribution of canopy openness was compared between sites S and SL using two-sample Kolmogorov–Smirnov tests, with $P < 0.05$ considered statistically significant.

RESULTS

Canopy openness after logging activities

In the primary forest, the calculated CO for all of the photography points was less than 5% and the mean CO was 1.79 ± 0.95%. Mean calculated CO values were 7.57 ± 6.63% and 7.88 ± 6.55% at the S and SL sites, respectively (Table 3-2).

According to the Kruskal–Wallis test, the mean CO of the primary forest was low compared to those of the two logging sites; no significant difference in CO was found between sites S and SL. In the two logged-over sites, the standard deviation suggested large differences in CO within each site. CO ranged from 0.27% to 23.82% at the S site and from 0.39% to 27.82% at the SL site. Fig. 3-2 shows the distribution of the calculated CO at each site, using two fractional scales. Large CO values were more frequent at site SL compared to site S. However, no significant difference in the CO distribution was found between sites S and SL using the Kolmogorov–Smirnov test.

The effect of logging on the canopy was strongly correlated with logging trails (Fig. 3-3).

The distribution of CO values was dependent on the logging activity conducted in the plot. Comparison of the CO values measured for each disturbance element showed a significant effect of logging activities on light conditions (Fig. 3-4). The mean CO was lowest at intact photography points at both sites S and SL. At site S, the mean CO was highest at the skid trail photo points. In contrast, at site SL, there was no significant difference among the elements, and the strip cutting treatment altered the light conditions.

In strip cutting line, mean CO was 11.71 ± 6.6% from all photography points. No significant differences were detected among the three lines (Table 4-2). However, considerable variation in CO was noted within each line. CO ranged from 2.25% to 24.82%. In some points, calculated CO values were almost the same as those in stands with closed canopies. However, many photography points had higher CO values. In addition, in each line, CO changed gradually and showed a wave-shaped trend (Fig. 3-5).

Correlation between canopy openness and sun fleck duration

Pearson's correlation coefficient analysis found a significant correlation between the CO value and cumulative sun-fleck duration for 1 year at the three sites and strip cutting line (Fig. 3-6). From the multiple comparisons, there were statistical differences in the slope among three sites and strip cutting line. The slope was highest in site S, followed by site SL, and followed by strip cutting line. Lowest slope was found in site PF.

DISCUSSION

Effects of logging activity on light conditions on the forest understory

Mean CO in primary forest stands was very low (<5%), which is explained by the presence of high multilayer canopies (Silbernagel and Moeur, 2001; Romell and Karlsson, 2009). In the two logged-over forests, logging activities and strip cutting treatment induced major changes in light conditions. Both in site S and SL, skidding and accompanying logging gaps changed the light condition significantly.

Skidding was the largest factor altering the light condition. In logged-over forest, when 8–15 trees are extracted per hectare, typically 15–40% of the area is traversed by bulldozer paths (Chai, 1975; Jusoff, 1991). Therefore, to suppress the impact on the light condition, it is necessary to reduce the number and area of skid trails. Planning efficient skidding and log pulling (winching) from skid trails were recommended (Supriyatno and Becker 1999).

Logging gap was also a main factor altering the light condition. The effect depended on logging intensity (Sist et al., 2003). And it was heterogeneous and varied enormously, being related to the size of each gaps. From the plot maps, there was variation in the size (Fig. 3-1), and it depends on the logged tree size and canopy condition of neighboring trees.

Although high CO was measured in strip cutting lines, significant effect on the canopy openness was not found in mean CO value and the distribution from the comparison between site S and SL (Table 3-2, Fig. 3-2).

In the two logged-over forests, mainly logging activities changed the light condition. Both in site S and SL, however, large CO values (i.e. 16-32%) were not found frequently. Efficiency of RIL for suppressing large canopy opening was reported in previous study (Sist et al., 2003). RIL was considered that functioned well for reducing the impact on canopy openness.

The strip cutting treatment did not affect the canopy openness as the whole forest stands. However, the effect of the treatment on the light condition was found in sun-fleck duration in the forest floor. Cumulative sun-fleck duration was strongly correlated with CO. Comparing three sites and strip cutting line, there were statistical differences in the slope of the regression. There was a difference in the cumulative sun-fleck duration for the same CO by different logging systems. The slope was highest in site S, and it in the strip cutting line was significantly low. It suggested that in same CO condition, the solar radiation was relatively short in strip cutting lines compared to logging gaps. The treatment scheme of strip cutting in this study was 3-m-wide cuts from north to south. With the sun pass from East to West, relatively short solar radiation was found in the "linear" gap created by strip cutting treatment. The slope in site SL was statistically low compared to site S. It was considered that affected by strip cutting treatment. Between site S and SL, there was no statistical difference in the canopy openness by the strip cutting treatment, however it was affected the solar radiation in forest floor. Various light conditions lead to different following seedling establishment and the species composition (Nifinluri et al., 1999). Strip cutting treatment might affect to the following seedling establishment.

Light conditions in strip cutting line

According to the biological characteristics of planted light demanding *Shorea* species, initial light availability is important (Clearwater et al. 1999). Strip cutting treatment was expected as one of the practical method to improve the light condition. However, large differences and a wave-shaped distribution of CO were observed in each strip cutting line (Table 3-2, Fig. 3-5). In this study, no canopy treatment such as girdling or pruning was performed after logging. Non-commercial and non-protected trees were only removed along 3-m-wide lines. The plots were set on rectilinear slopes with 14 degree slope in most steep line. Therefore, the differences in CO under the same strip cutting treatment were dependent on the abundance of neighboring trees and the canopy condition along the line. These initial differences in CO and following canopy closure can affect the survival and growth of planted seedlings. Canopy gaps close rapidly after at least 6 months in pioneer-dominated forests (Romell and Karlson, 2009). To reveal the appropriate light conditions for planted seedlings and enhance the line planting methods, it is necessary to monitor the canopy openness change and the relationship to the planted seedlings by continuous research.

Table 3-1 Topography at each site

Plot	Difference in slope position (m)	Slope aspect
PF1	11.8	South
PF2	13.9	Ridge from North to South
PF3	31.5	Southeast
S1	15.8	Northwest
S2	21.0	South east
S3	15.0	South
SL1	20.0	Northwest
SL2	16.5	Northwest
SL3	12.4	East
Strip cutting line 1	14.4	South
Strip cutting line 2	9.9	North
Strip cutting line 3	1.0	Almost flat

PF, primary forest; S, selective logging; SL, selective logging and line planting

Table 3-2. Summary of the mean canopy openness for each site and strip cutting line

Site	Plot	*N*	Mean	S.D.	Max.	Min.
PF	1	49	1.3	0.8	4.2	0.2
	2	49	1.9	0.9	4.7	0.4
	3	49	2.2	0.8	4.2	1.1
	All	147	1.8	1.0	4.7	0.2
S	1	49	4.2	3.9	13.1	0.3
	2	49	9.4	6.2	21.3	1.5
	3	49	9.1	8.0	23.8	0.3
	All	147	7.6	6.6	23.8	0.3
SL	1	49	8.9	5.6	19.5	0.5
	2	49	4.0	1.4	8.3	1.2
	3	49	10.7	8.5	27.3	0.4
	All	147	7.9	6.6	27.3	0.4
Strip cutting line	1	21	11.0	6.1	19.1	2.3
	2	21	11.7	7.4	23.8	2.8
	3	21	12.4	6.5	24.8	4.8
	All	63	11.7	6.6	24.8	2.3

PF, primary forest; S, selective logging; SL, selective logging and line planting

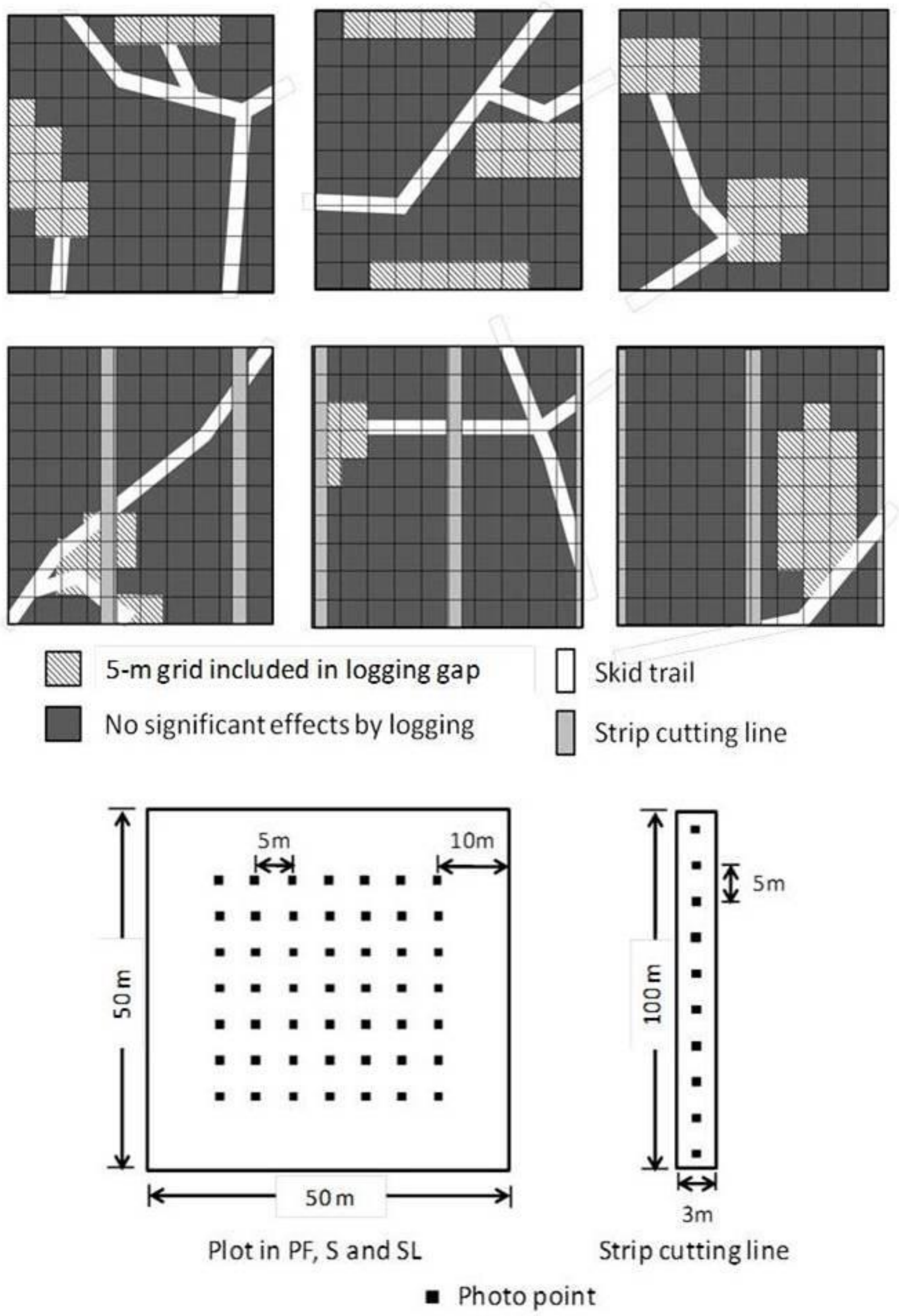

Fig. 3-1. Treatment maps for the S and SL sites (above) and sample plot schematic showing photography points (below).

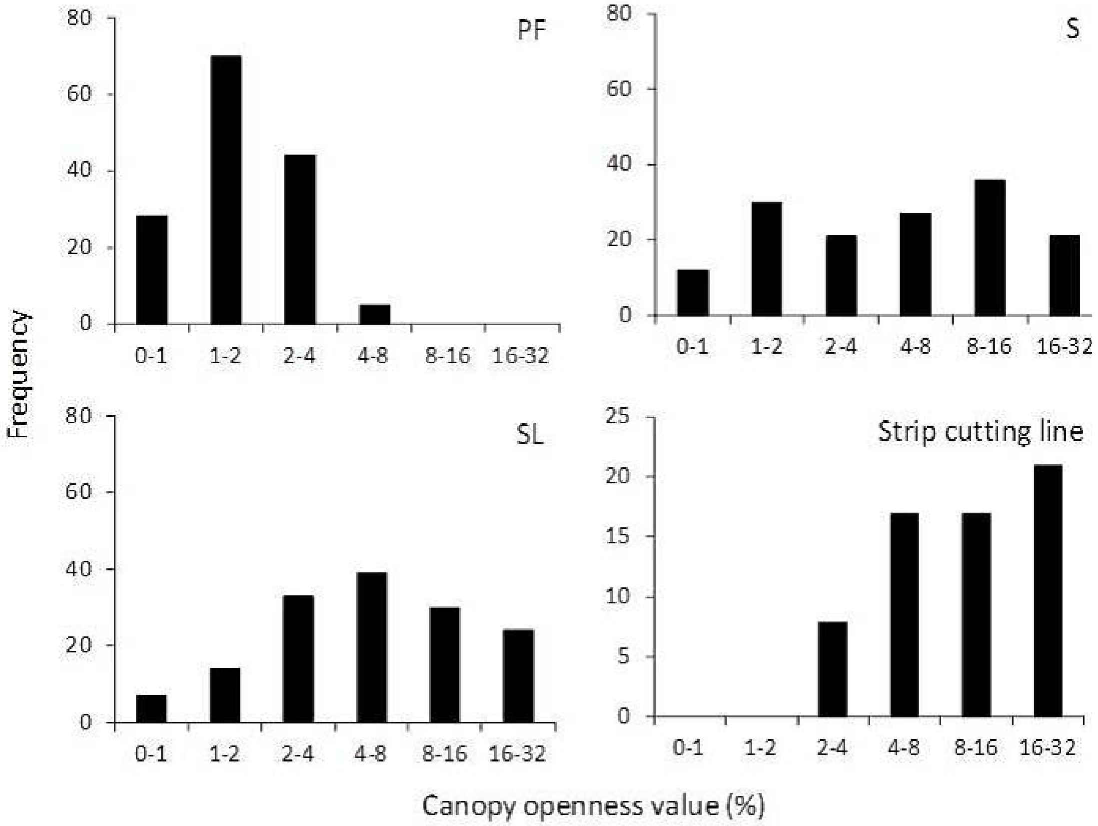

Fig. 3-2. Frequency distribution of the canopy openness (%) for all photography points at each site. PF, primary forest; S, selective logging; SL, selective logging and line planting

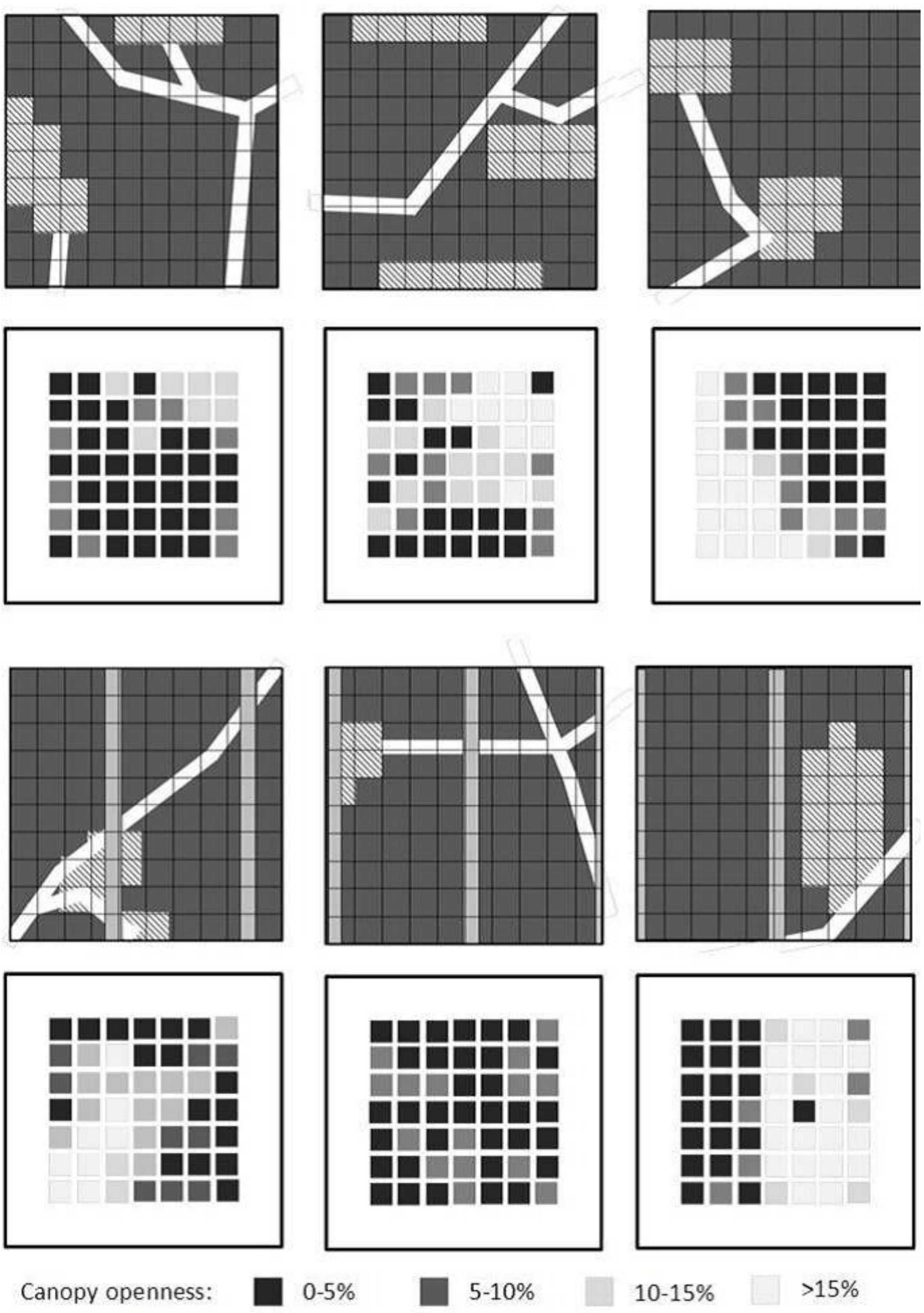

Fig. 3-3. Logging trail maps and distributions of canopy openness values calculated from those images. Graph legends for the plots are same as Fig. 3-1.

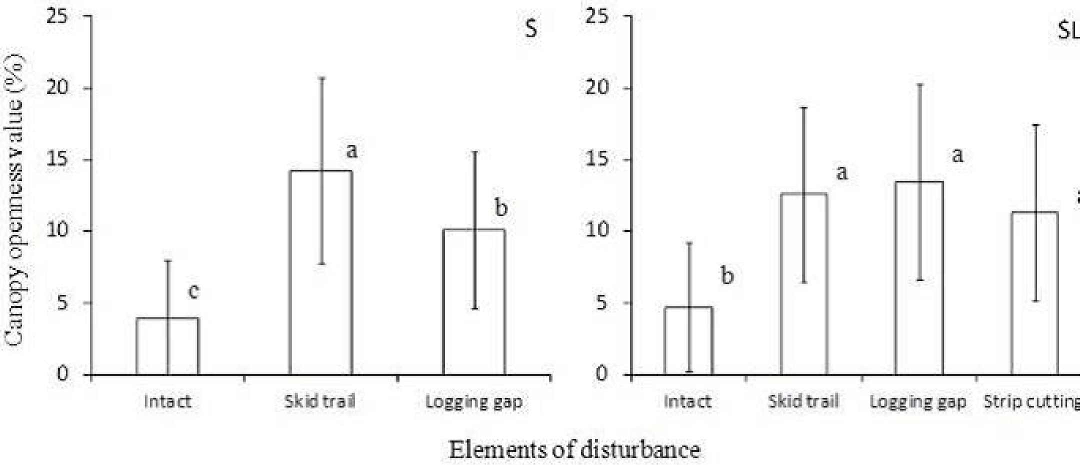

Fig. 3-4. Comparison of canopy openness among the logging elements in the selective logging (S) and selective logging and line planting (SL) sites. Different letters indicate statistical differences using Tukey’s test.

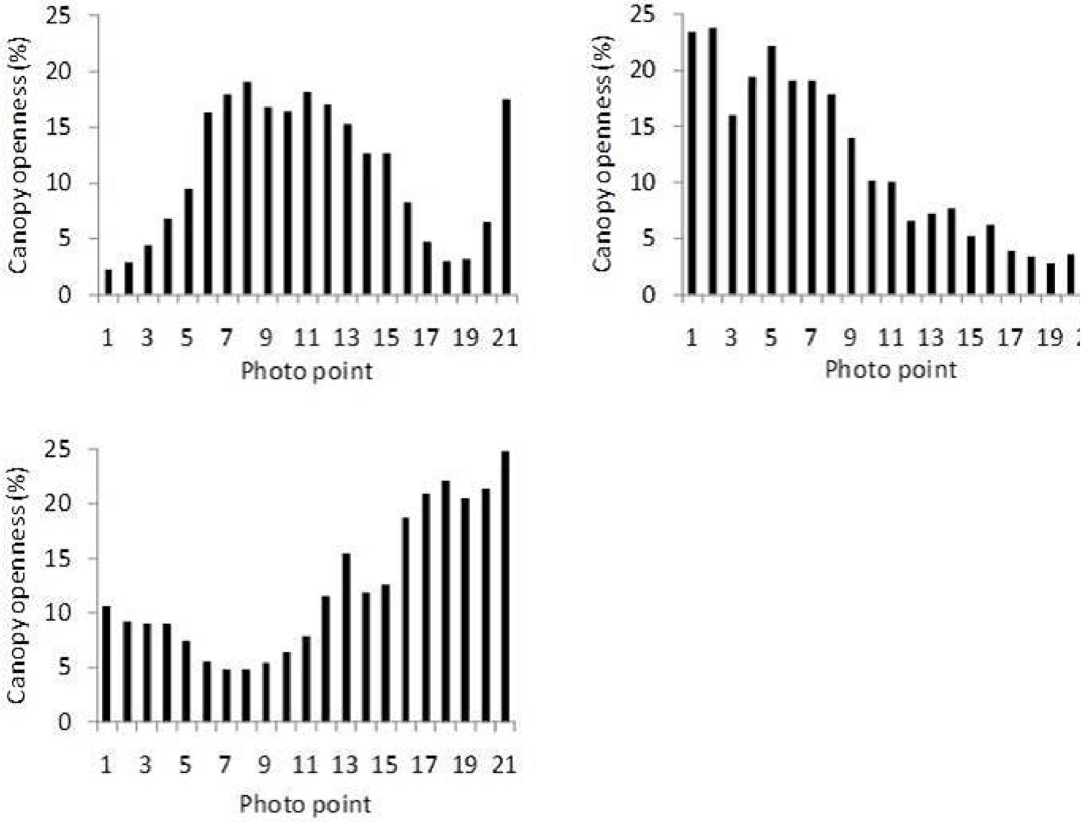

Fig. 3-5. Distribution of canopy openness in each line. Photo points were counted from the south end of each line.

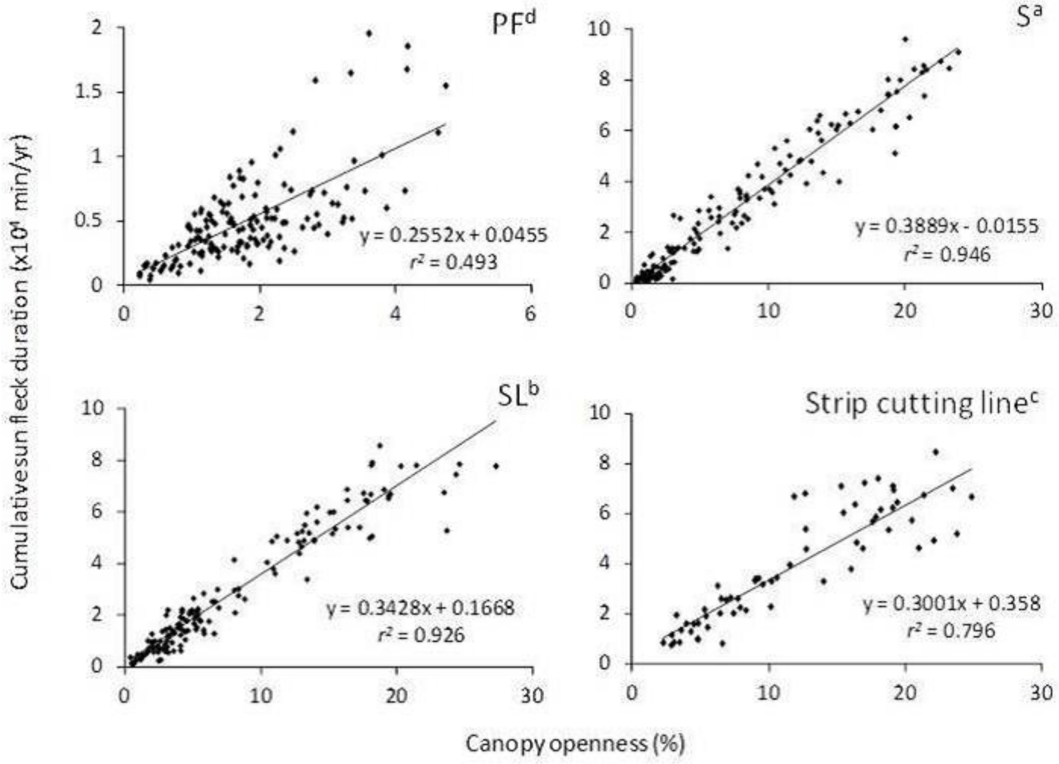

Fig. 3-6. Scatter diagram of the correlation between the calculated canopy openness and cumulative sun-fleck duration for 1 year at each photography point in the primary forest (PF), selective logging (S), and selective logging and line planting (SL) sites and strip cutting lines. Different letters attached to site name indicates statistical difference using Bonferroni's test.

Chapter 4 Effects of contrasting selective logging managements in the light environment and line-planted seedlings

INTRODUCTION

In chapter 3, from the hemispherical photography in primary forest and two managed forests with or without line planting, the light condition in forest floor changed significantly even using RIL (Inada et al. 2013). And there was no difference in mean canopy openness (CO) between two managed forests with or without 3-m wide strip-cutting treatment. In a strip-cutting line, although the treatment was efficient to alter the light condition of planted seedlings, there was a large variance of CO among 5-m spacing photo points.

In line planting system, mainly red or yellow meranti species (e.g. *S. leprosula, S. johorensis* and *S. parvifolia*) are planted in the planting lines because of their commercial value. They commercial *Shorea* species are light demanding members in Dipterocarpaceae (Clearwater et al. 1999; Dent & Burslem 2009; Pamoengkas 2010). Numerous previous studies report that some degree of canopy opening improves the growth of those *Shorea* trees (Bebber et al. 2002; Kuusipalo et al. 1996; Hattori et al. 2013).

However, for the planted trees, the efficiency of strip-cutting treatment and the appropriate light condition for their growth have not been evaluated based on the monitoring for the growth of planted trees in relation to the light condition change.

In usually, after logging, the gaps created by logging activities (logging, landing and skidding) are occupied by light demanding pioneer *Macaranga* species (Slik, R. Verburg, et al. 2002; Howlett & Davidson 2003; Romell et al. 2009). The pioneers may invade into the planting lines and it may inhibit the growth and survival of line-planted seedlings.

For planted *Shorea* seedlings, the light condition in initial period must be important. In other line planting test, the mortality was high immediately after planting (Ådjers et al. 1995; Matsune et al. 2006). For the progress of line planting system, it is necessary to assess the effect of light condition change on the growth of planted seedlings especially in initial period after planting.

In addition, in chapter 3, it was clarified that the effect of the strip cutting treatment on the following light condition as forest stand scale.

Although the effect of strip cutting on canopy openness was not found, in the linear gaps opened by strip cutting, the sun-fleck duration differed from the gaps with logging gaps.

To evaluate the effect of line planting system on the forest dynamics, it is also necessary to monitor the light condition change in the managed forests with or without line planting treatment.

In this study, I continued the hemispherical photography for 31 months from Oct. 2011 and evaluated the light condition change in two managed forests with or without the line planting treatment. Then the effects of light condition for planted seedlings survival and growth were examined in the line planting system.

MATERIAL AND METHODS

We used same study site used in Chapter 3. In this study, we continued the hemispherical photography in Oct. 2012 and Apr. 2014 in the same study sites, plots and the methodology to Chapter 3.

Monitoring of planted seedlings in the plating lines

In SL site, *Shorea* seedlings were planted in 2.5m-spacing in Dec. 2011, after first light condition assessment. Two of three lines (Pline 1 & 2), planted species are *Shorea johorensis* and *S. leprosula* was planted in another line (Pline3). From second photography, the survival and growth of planted trees 10 months after planting were monitored at the same time. The growth was monitored by diameter at ground level

In the planting line, the hemispherical photo points were set in 5-m intervals. Then seedlings planted between two photo points, the average CO of neighboring two photo points was used for evaluation of the correlation of light condition and the growth of planted seedlings. To assess the correlation between the light condition and seedling growth, multiple regression was conducted. Objective variable was seedling growth, explanatory variables were the change in CO values from 2011 to 2012 and 2014, Initial CO in 2011 and site condition at planting points recorded in 2011 (skid tail or logging gap). Site condition was categorical variable (0 or 1).

Data analysis

Statistical analysis was conducted using SPSS ver. 12 (SPSS, Chicago, USA). To compare the impact of management, the mean COs among study sites and logging elements in each site were compared by Steel-Dwass test. And to assess the light condition change, the correlations between initial CO measured in 2011 and the reduction until 2012 and 2014 were analyzed by Spearman's test. Statistical significance was detected by $p < 0.05$.

RESULTS

Canopy openness change from 2011 to 2014 in each site

In 2011, after logging and strip cutting treatment, there was significant impact on the light condition (Fig. 4-1). Mean COs in each site and planting lines were 1.79 ± 095%, 7.57 ± 6.63%, 7.88 ± 6.55% and 11.17 ± 6.6%, respectively. Compared to the PF site, mean CO was statistically higher in S, SL site and planting lines. Between two managed forest sites, there was no statistical difference. Highest mean CO was found in planting lines (Steel-Dwass test, $p<0.05$).

From 2011, the mean CO decreased significantly to 2012 and 2014 in two managed sites and planting line. Until May 2014, mean COs in each site and planting line changed to 1.28 ± 0.61%, 2.2 ± 1.54%, 3.14 ± 1.69% and 5.13 ± 3.23%, respectively. Mean CO decreased significantly excluding PF site. The mean CO was still higher in two managed forests and planting lines compared to PF site (Steel-Dwass test, $p<0.05$), and there was statistical difference between S and SL site. Highest mean CO was found in planting lines.

From 2011 to 2012 or 2014, for each photo point, following CO reduction were correlated to initial CO in 2011 (Spearman's test, $p < 0.01$), and the correlation was more significant until 2014 than until 2012 (Fig. 4-2)

Under each disturbance element, skid trail, logging gap and planting line, high CO was found in 2011 (Fig. 4-3). In S site, the highest CO was found in skid trails. In SL site, there was no difference between skid trail and logging gap, and the mean CO was slightly low in planting line compared to other two disturbance elements.

Until May 2014, the mean CO in skid trail and logging gap decreased to intact level in S site, however in SL site, the CO was still high in disturbed photo points.

In SL site, the Fern dominated a logging gap at plot SL3. The domination by fern could not be reflected to photography taken at 1.3-m camera lens height and it caused the high CO in the site. Excluding the SL3 plot, mean CO in each disturbance element was slightly higher in SL site than in S site, and mean CO was highest in planting line (Fig. 4-4). However, from the comparison of three sites and planting line, the mean CO was statistically higher in SL site than in S site. Between S and SL site, the statistical difference in mean CO arose about three years after management.

From the tree census in 2011 and 2012 at a planting line, tremendous seedlings established only one year after disturbance ($n=510$). The establishment frequently along the skid trail, bull-dozer pass and in logging gap, not significant in strip cutting line (Fig. 4-5).

Planted-seedling growth in relation to light condition change

From Oct. 2012 to May 2014, the survival rate of plated *S. johorensis* (n=82) and *S. leprosula* (n=41) were 87% and 81.8%. Mean diameter of *S. johorensis* and *S. leprosula* increased from 1.1 ± 0.27 cm and 0.86 ± 0.28 cm to 1.97 ± 0.56 cm and 1.43 ± 0.53 cm, respectively.

From the multiple regression for the seedling growth, statistically reasonable correlation was not found. However about the CO change from 2011 to 2012 and the seedling diameter growth from 2012 to 2014, there might be the suppression of growth by CO reduction (Fig. 4-6). The diameter growth from 2012 to 2014 was decreased with the reduction of CO from 2011 to 2012.

DISCUSSION

Light condition change after logging management

In primary forest, the mean CO was quite low as found in previous studies (Bischoff et al. 2005; Nicotra et al. 1999; Yamada et al. 2014). The low CO can be explain by the multilayer canopies (Silbernagel & Moeur 2001; Romell et al. 2009). Logging those canopy trees altered the light condition significantly. For 31 months after management, the CO decreased significantly and the reduction was significant in photo points where high CO measured in 2011. Only 31 months, the forest floor closed even in largely opened point. As found in the tree census along a planting line, after large canopy opening by management, the forest floor closed by pioneer seedling establishment rather than by crown expansion by neighboring residual trees.

Higher CO induced the pioneer seedling invasion (Slik, R. Verburg, et al.

2002), and canopy closure, and sometimes it was dominated by fern and inhibited the tree seedling establishment.

In May 2014, the mean CO was statistically different between the S site and SL site, without or with line planting after logging. From the CO change under each disturbance element, skid trail, logging gap and planting line, the highest mean CO was found in skid trails in S site in 2011. When 8-15 trees/ha are extracted, typically 15-40 % of the area is traversed by bulldozer paths (Chai 1975; Jusoff 1991). And in the skid trails, plant growth was poor compared to gap (Howlett & Davidson 2003). Therefore reducing skidding by RIL was efficient for mitigating to the light condition.

From 2011, even in skid trails, mean CO decreased to intact level in S site until May 2014. In SL site, the mean CO under each disturbance element was higher in logging gap and skid trail than in planting line in Oct. 2011. However, the mean CO in planting line became the highest in May 2014, excluding a plot dominated by fern. Strip cutting treatment kept the gap opened. Compared to logging gap and skid trail, the strip cutting might be not destructive for the forest stand. The treatment was conducted using skid trails without bulldozer. In the lines, commercial and large trees were not cleared. Then in the planting lines, the seedling establishment was frequent in and around other skid trail and logging gap, it was not significant in photo points intact from management.

The impact of strip cutting treatment for light condition was considered that smaller than other logging gap and skid trail. And it was not occupied by pioneer seedlings. Therefore, the mean CO in planting line was still high and it cause the difference between S and SL site in 2014. Although the effect of strip cutting treatment on the forest floor light condition was not significant, it remained longer and it might affect to the following dynamics and planted seedlings.

Effect of light condition changes on the planted seedlings

For planted trees, excess light can cause to reduction of growth by photoinhibition and mortality by changing microclimate (ITTO, 1989; Sasaki and Mori, 1981). And the survival and growth were reduced under deep shading (ITTO, 1989; van Oorschot et al. 1996). However, in this study, the growth was not explained well from the multiple regression analysis using the CO, those change from 2011 and disturbance effects (logging gap and skidding). From growth analysis, the CO reduction, that is seedling establishment in the planting lines might suppress the growth of planted seedlings. The CO reduction from 2011 to 2012 was probably caused by seedling establishment, and those seedlings could become the competitors of planted seedlings. The CO reduction was significant in photo points high CO was measured, then, tremendous seedlings established and inhibited the growth of planted seedlings from 2012.

The effects of strip cutting treatment for altering light condition of planted seedling differed widely. From the three years monitoring, following closure by pioneer seedling establishment caused by excess canopy opening often induced suppression of the growth of planted seedlings. Mortality on planted seedlings by line planting test was frequently in initial period after planting (Ådjers et al. 1995; Matsune et al. 2006). The growth suppression might induce the mortality of planted seedlings.

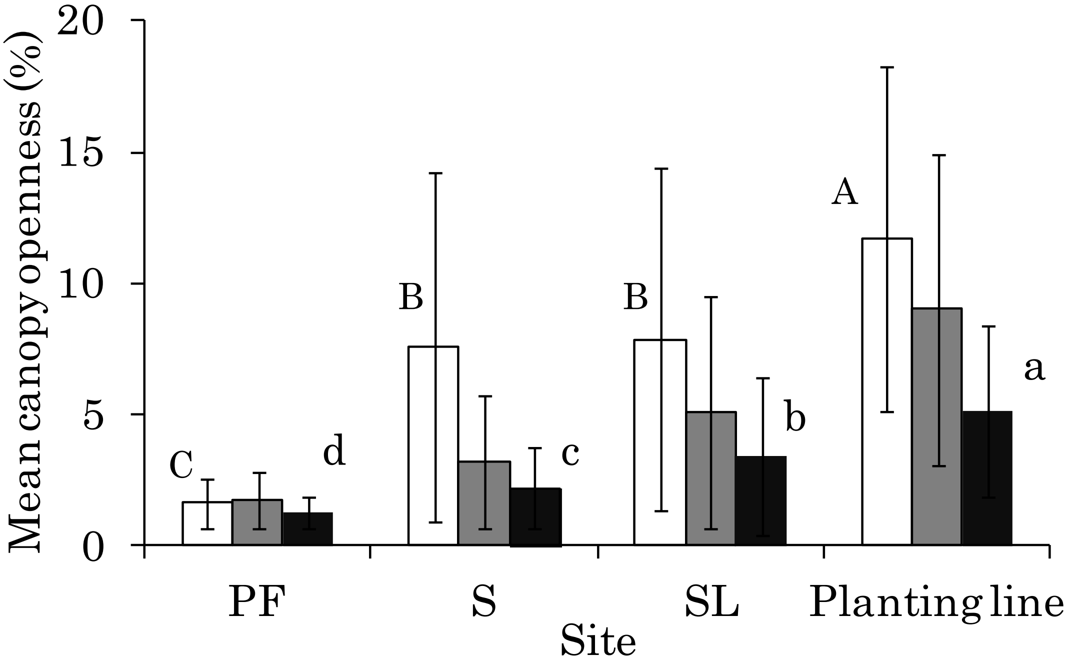

Fig. 4-1. Mean CO in each site and planting line measured in 2011 (blank bars), 2012 (shaded bars) and 2014 (filled bars). Error bars indicated the S.D.

Different letters in capital and small letter shows statistical difference in 2011 and 2014. (Steel-Dwass test, $p<0.05$)

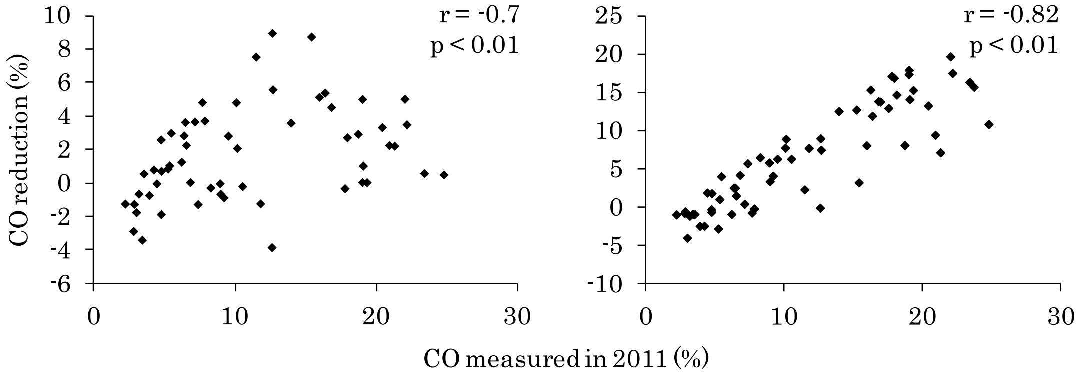

Fig. 4-2. Correlation between initial CO measured in 2011 and CO reduction to 2012 (left) and 2014 (right). The correlations were tested by Spearman's method.

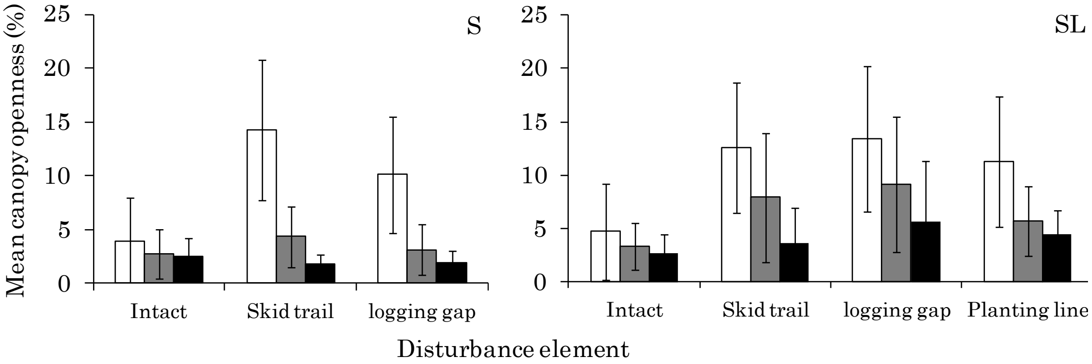

Fig. 4-3. Mean CO under each disturbance element measured in 2011 (blank bars), 2012 (shaded bars) and 2014 (filled bars). Error bars indicated the standard deviation.

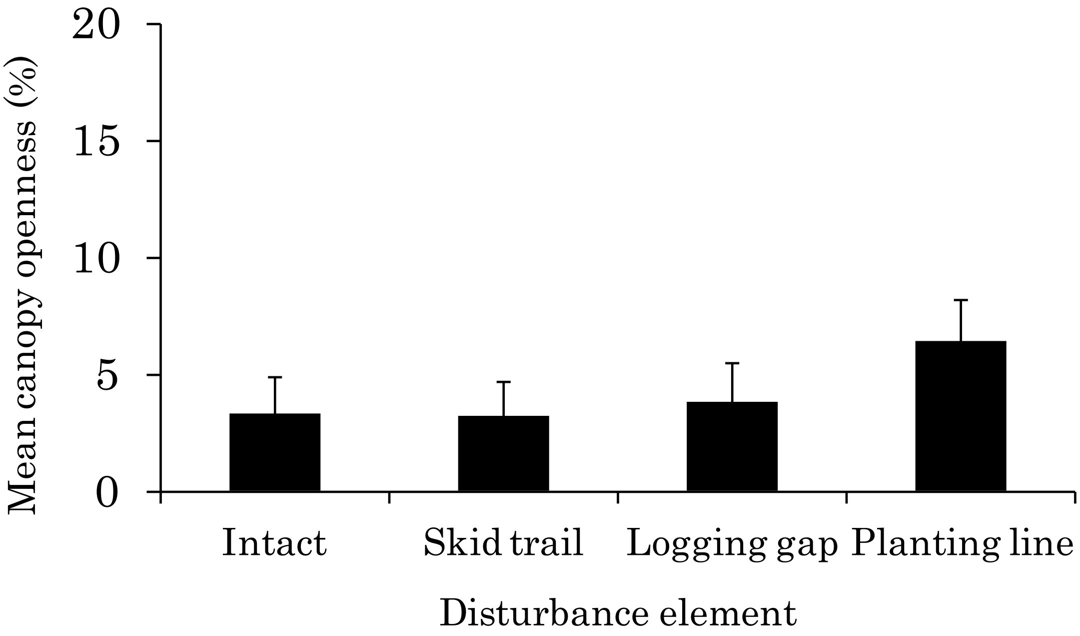

Fig. 4-4. Mean CO under each disturbance element measured in SL site excluding SL3 plot in 2014. Error bars indicated the standard deviation.

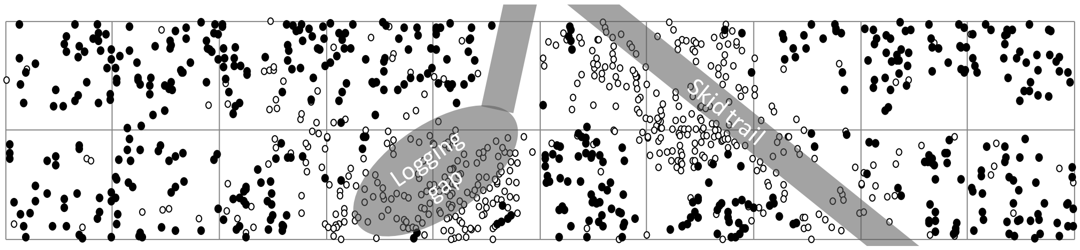

Fig. 4-5. The position of all trees > 1 cm DBH in 2011 (filled dot) and seedlings newly established until 2012 (blank dot) in a 20×100 m line transect set along a planting line.

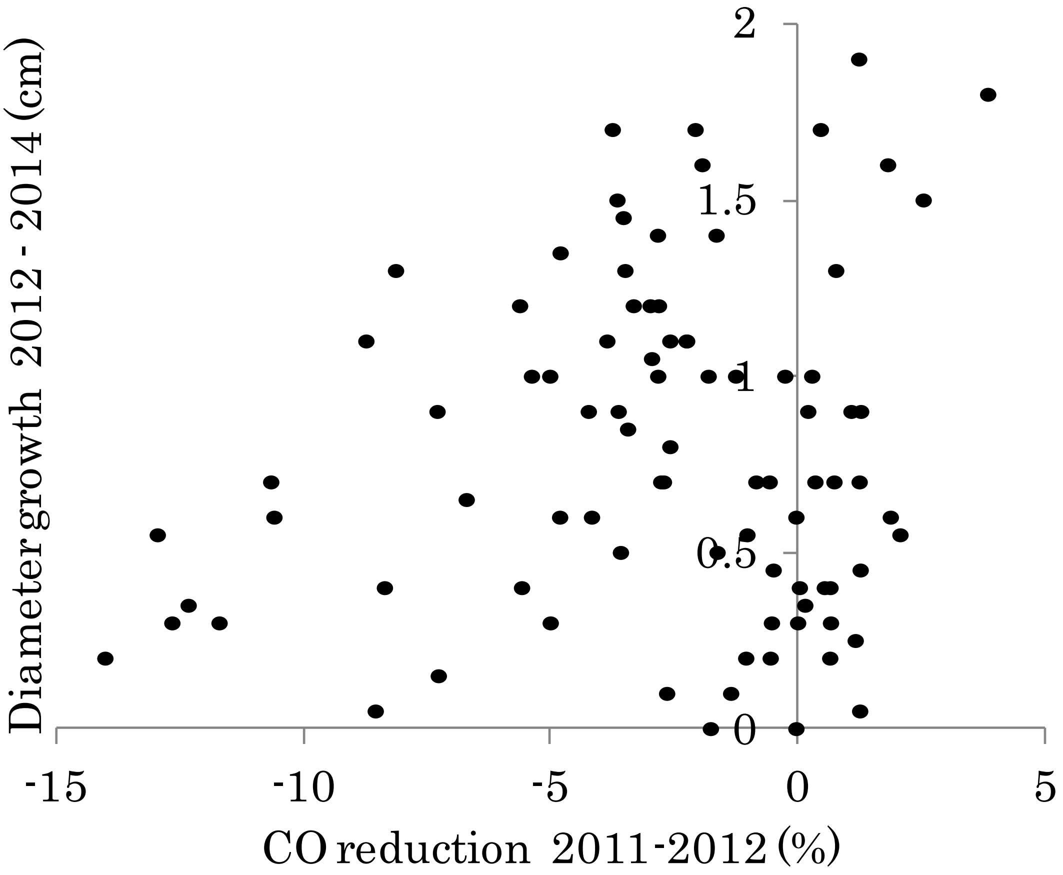

Fig 4-6. Correlation between CO reduction from 2011 to 2012 in each photo points in planting line (n=63) and diameter growth from 2012 to

Chapter 5 Neighboring tree effects on the survival and growth of line-planted *S. johorensis*

INTRODUCTION

From chapter 3 and 4, under same 3-m strip cutting treatment, there exists a large variance in the light conditions in a planting line. The initial difference in the light condition would affect the following survival and growth of planted trees. The light conditions in forest floor are determined by the complex spatial structure and dynamics of the multi-layer canopy (Bebber et al. 2002; Bunyavejchewin et al. 2003; Okuda et al. 2003). In the line-planting system, the planted seedlings are suppressed by the remnant trees along the planting lines (Pamoengkas et al. 2014), particularly in the initial years after planting. In other words, in the absence of those “neighboring” trees, the planted seedlings may grow rapidly and reach the main canopy. The suppression from neighboring trees in initial after planting can decide the long-term growth of planted trees.

To evaluate the importance of initial growth for the long-term growth and survival of planted *S. johorensis,* a monitoring study was conducted over a period of 11 years. Additionally, to evaluate the effects of neighboring trees on the planted trees, diameter at breast height (DBH), tree height and crown expansion are useful for evaluating the growth and condition of the trees. The neighboring trees' upper crown often inhibited the growth of understory by casting shade (Getzin et al. 2008). For dipterocarps, the growth was obviously correlated to their crown area and light interception by neighboring trees (King et al. 2005).

Computer modeling is a useful method for assessing the crown condition (Silbernagel and Moeur 2001). *SExI-FS* (spatially explicit, individually based forest simulator, Harja and Vincent 2008) enables the characterization of trees by modeling the three-dimensional spatial structure (Manson et al. 2006). In the monitoring plots, 11 years after implementation of the line-planting system, we assessed the crown condition of the planted *Shorea johorensis* by modeling the three-dimensional spatial structure.

For the light demanding *S. johorensis*, the coverage by neighboring tree crowns would inhibit their survival and growth, then it is important to assess the correlation between the crown condition of planted trees and their performance. The planted trees were planted in 5-m intervals along the 3-m wide strip cutting lines to improve their light condition. However, the width of strip cutting and planting interval ahve not been evaluated. It is also needed to evaluate the efficiency of planting scheme from the assessment of planted trees.

Thus, to evaluate the efficiency of the line-planting system, this study assessed the growth and survival of the planted trees in relation to the initial growth influenced by the initial light condition after strip cutting. Moreover, to assess the effects of canopy structure along planting line, the crown condition of the planted trees was evaluated from a three-dimensional model of the spatial structure of the forest.

MATERIAL AND METHODS

Study area and monitoring scheme

The study site was same to RIL+LP/S site in chapter 2. The planted species was *S. johorensis*. The seedlings, grown for 8-10 months under shade netting in the nursery, were planted at a 5-m spacing along the central lines in the strips. Those seedlings were grown from seeds and transplanted from plastic bags (15 cm dia. 25 cm height). The mean basal diameter and standard deviation at the time of planting was 0.35 ± 0.1 cm.

We utilized the monitoring data collected by Sari Bumi Kusuma for up to 10 years after planting, and continued the monitoring, and conducted a tree census 11 years after planting. At the study site, three 1-ha (100 × 100 m) plots were selected to include as many planted seedlings as possible for monitoring after logging and planting in 2000.

The ground topography was quantified by measuring the difference in elevation of a 10-m grid intersection with a LaserAce Hypsometer (Measurement Devices, Ltd. York, U.K.). The differences in the highest and lowest elevations in the each of the three 1-ha plots were 21.0, 21.9 and 16.8 m, respectively. The topography in each plot was undulating. The above-mentioned schemes of planting and plot establishment resulted in a total of 105 seedlings per plot along the five planting lines, each of which had 21 planting points (Fig. 5-1). The line planting was conducted avoiding steep slopes, streams or small ponds, and the number of seedlings planted in each monitoring plot was 103, 98, and 105 trees, respectively.

The survival of the planted and other non-planted trees with a DBH ≥10 cm, and the diameter growth were recorded, eight times, in the year of planting, and 1, 2, 4, 6, 8, 10, and 11 years thereafter. The growth of the planted trees was measured using the diameter at base until the DBH reached 10 cm. After the tree had reached a DBH of 10 cm, the DBH growth was monitored.

At the eighth measurement, 11 years after planting, we measured the DBH of all planted trees including those with DBH <10 cm. In the plots, after logging and planting, newly recruited lianas, shrubs, ferns, and other large herbaceous plants, and pioneer tree seedlings were cut every year by machetes to eliminate competitors to the planted seedlings. This weeding treatment was not conducted at the time of selective logging and line planting. Thus, the survival and growth of planted trees were monitored under the intensive management after line planting. The importance of the initial growth for the long-term survival and growth of the planted trees was assessed using the diameter growth at base 1 year after planting from monitoring data (2000-2001).

Morphological measurements and three-dimensional modeling

A morphological assessment of the planted trees and a tree census for modeling of the three-dimensional spatial structure of the monitoring plots were conducted 11 years after planting. In the three 1-ha monitoring plots, for each tree; *i.e.,* all 234 planted *S. johorensis* and 1488 other non-planted trees ≥ 10 cm DBH, the coordinates in the plots, DBH, tree-top height, crown depth (crown vertical length from the tree top to the lowest branch), and crown width in four directions from the trunk were measured (Fig. 5-2). The tree-top height and crown depth were measured with a LaserAce Hypsometer. The crown width was measured using a measuring tape.

Using these data, the three-dimensional spatial structure was described using *SExI-FS*. Each tree crown was constructed based on triangulation algorithm, assuming the tree crown as a polyhedron formed by the aggregate of triangles using measurement data of crown depth and crown widths to four directions (See *SExI-FS* Documentation: http://www.worldagroforestry.org/sea/Products/AFModels/SExI).

The model outputs were used to estimate the crown illumination (CI) level of the planted trees, following Dawkins and Field (1958):

1. No direct sunlight: the crown receives only light filtered through the crowns of other trees.
2. Mostly sidelight: the crown receives no direct light vertically. Part of the crown receives direct sunlight laterally.
3. Some overhead light: part of the crown is exposed to vertical light, whereas part of it is shaded from above.
4. Full overhead light: upper part of crown fully exposed to overhead light, but the sides of crowns may or may not receive direct sunlight laterally.

To estimate the CI level, trees planted in stands <10 m from the border were excluded to avoid the effects of trees located outside the plot (Fig. 5-1).

Data analysis

Statistical analysis was conducted using PASW ver. 17 (SPSS, Inc. Chicago).

We used parametric and nonparametric tests depending on sample size and distribution. A p-value <0.05 was considered to indicate significance. The survival rate and DBH of the planted trees among the three monitoring plots 11 years after planting were compared using one-way ANOVA. To test for a relationship between planted tree survival 11 years after logging and the initial growth (diameter growth at base during 2000-2001), logistic regression analysis was used. In logistic regression, the objective variable was the probability of survival of planted trees until 11 years after planting. The survival is a binary state variable expressed by 1 (survive) or 0 (dead). Initial growth was used as a variable to predict the probability of survival. This logistic regression analysis was conducted using statistic software, R (ver.3.1.1). R was only used for the logistic regression analysis.

To evaluate the effect of initial growth on following growth, the correlation between initial growth and DBH 11 years after planting was assessed by Spearman's test.

The allometric correlations of the planted *S. johorensis* for morphological characteristics, DBH, tree height, and crown expansion were detected using Pearson's correlation coefficient analysis.

Among the trees classified by the four CI levels, the average DBH 11 years after was compared by Steel-Dwass test. And the correlation between initial growth and CI level of each tree was assessed by Spearman's test.

Values are represented as the mean ± standard deviation (SD).

RESULTS

Survival and growth of planted trees

In 2000, after logging and line planting, the average tree density and basal area for non-planted trees with DBH ≥10 cm in the three monitoring plots were 258 ± 1.0 trees/ha and 16.0 ± 3.0 m^2/ha, respectively. Eleven years later, these had increased to 373 ± 40.1 trees/ha and 23.4 ± 3.4 m^2/ha, respectively, excluding the planted trees. In addition, planted *Shorea johorensis* with DBH ≥10 cm contributed to the stand growth with 69.7 ± 6.5 trees/ha and 1.8 ± 0.2 m^2/ha, 11 years after planting.

Eleven years after planting, the average survival rate of planted *S. johorensis* was 77.6 ± 8.1%. The mortality was found almost constantly for 11 years although no mortality was recorded for the period 4-6 years after planting (Fig. 5-3).

The mean DBH values in the monitoring plots were 17 ± 6.4, 15.8 ± 4.6 and 17.4 ± 5.8 cm. There were no significant differences among the three plots in the survival rate and average DBH. In each monitoring plot, we found considerable variation in DBH (Fig. 5-4). The DBH of all planted *S. johiorensis* ranged from 5.3 to 33.6 cm.

For the planted *S. johorensis*, the increment in diameter at base 1 year after planting (initial growth) ranged from 0.01 to 2.39 cm. The logistic regression analysis revealed that initial growth affected the probability of survival at 11 years after planting (Fig. 5-5). The regression predicted that the probability of survival increased with the initial growth. From the regression, the probability of survival decreased to below 50% for the trees that grew less than 0.13 cm in the diameter at base for 1 year after planting.

For the planted trees, the DBH at 11 years after planting significantly increased with the initial growth (Fig.5-6). These results indicated that the initial growth of planted *S. johorensis* influenced following survival and growth.

Morphological characteristics of planted trees and canopy conditions

For the planted *S. johorensis*, a significant correlation was found between the tree-top height and DBH. The crown depth and crown width were also proportional to DBH. The crown width of each planted *S. johorensis* was calculated from the mean of the crown width from the trunk in four directions. Trees with a larger DBH had a greater tree height and crown width.

The morphological characteristics of all other non-planted trees with a DBH ≥10 cm were also assessed. Based on the coordinates and morphological characteristics of the trees, the three-dimensional spatial structures of the monitoring plots were modeled using the *SExI-FS* software (Fig.5-7). Some of the planted trees were exposed to direct sunlight vertically. Otherwise, some of them were surrounded by neighboring trees laterally and suppressed by larger trees vertically.

From the three-dimensional model, the CI levels were assessed by eyes for each planted tree standing ≥10 m from the boundary of the monitoring plots to avoid the effects of trees outside the plots (n = 113). The average DBH differed significantly according to the order of the CI level by Steel-Dwass test (Fig. 5-8). The smallest DBH values were found in CI level 1. Larger DBHs were found in CI levels 3 and 4, and there was no significant difference in DBH between these two CI levels.

Furthermore, the CI level 11 years after planting was related with initial growth. Trees showing high initial grow after planting was in CI level 4 11 years after planting.

DISCUSSION

Over the 11-year period, the logged forest stock increased and the planted trees contributed to restocking the density of dipterocarps, regardless of the different microsite conditions among the three monitoring plots (Fig. 5-8). However, the contribution of the planted trees to the basal area remained low 11 years after planting. Many of the planted trees were still growing and remained small. The survival rate of the planted trees was higher than reported previously (Ådjers et al. 1995; Matsune et al. 2006). Including planted trees with DBH ≥10 cm, stand stocks at 11 years after planting increased from 373 ± 40.1 trees/ha and 23.4 ± 3.4 m^2/ha to 452 ± 38.0 trees/ha and 24.9 ± 3.5 m^2/ha, respectively. The line planting was effective in enhancing the potential for regeneration of the stand stock and desired tree species.

High survival rates and steady growth were found in all three monitoring plots under intensive management involving annual weeding and 3-m strip-cutting treatments. Removing understory competitors by weeding enhances seedling growth (Bebber et al. 2002). And the difference in light conditions along the planting lines after the strip-cutting (Inada et al. 2013) was considered as a factor affecting to the growth of the planted *S. johorensis.* As seen in the light condition in planting lines, there was a wide range in diameter growth at base 1 year after planting (0.01–2.39 cm).

The initial growth was a good predictor of subsequent survival and growth. For 11 years after planting, planted trees showing higher initial growth showed higher probability of survival. Mortality tended to occur in such planted trees that showed poor growth. And initial growth also affected to the following growth. Trees showing higher initial growth after planting marked larger DBH 11 years after planting.

From the three dimensional modeling and scoring CI levels, the DBH value decreased with increased cover from neighboring trees, and trees exposed to more vertical light showed greater DBH. In the larger planted trees, which were classified into CI levels 3 and 4, the tree tops were exposed to direct solar radiation. Light-demanding *Shorea* species such as *S. johorensis* require a small gap so that the tree top is exposed to direct sunlight, which is known as a "chimney environment", for their optimum growth (Tuomela et al. 1996). Vertical light availability from the canopy gap allowed the planted seedlings to grow rapidly. In contrast, planted trees in CI levels 1 and 2, in which the tree top was covered by the crowns of neighboring trees, exhibited markedly suppressed growth. Neighboring trees filled the gap by lateral expansions of the crowns and prevented vertical light from reaching the planted trees.

The planted tree's CI level 11 years after planting was related to initial growth. Trees showing higher initial growth after planting were in better CI levels and marked larger DBH 11 years after. It suggested that the relationship between planted trees and neighboring tree crowns did not changed frequently. In other words, for planted trees, the neighboring tree in the initial state after planting influenced the later survival and growth, at least 11 years after planting. From the survival curve for 11 years, the mortality event was frequent during 4-6 years after planting. In previous planting tests, the mortality was significant for the first 2 years after planting (Matsune et al. 2006, Hattori et al. 2013). In the monitoring plots, removing competitors by understory weeding prevented the mortality in the early period after planting. The 3-m wide strip cutting treatment before planting was thought to be efficient to promote the survival and growth for some of planted trees by reducing the suppression from neighboring trees. However, for other planted trees suppressed by neighboring trees, with increasing light requirement towards their maturity (Mauricio 1987, Mori 2001), their growth were thought to be suppressed, resulting in the mortality during 4-6 years after planting.

Therefore, in a line-planting system, increasing and sustaining the vertical sunlight availability is necessary to ensure the survival and promote the growth of the planted trees. Canopy treatments; *e.g.*, pruning or girdling of neighboring trees which inhibited the planted tree growth laterally and vertically, are effective in improving forest floor light conditions (Matsune et al. 2006). Additionally, on-going maintenance in this study, strip cutting and annual weeding treatment must be carried out effectively to ensure the survival and growth of planted trees. However, such maintenance methods are costly and impractical for large forest management areas (Ruslandi et al. 2014). In our study, we observed no difference in the survival rate and growth of the planted trees among the three plots, and some trees grew rapidly and expected to reach harvestable size, 40 cm DBH, in the next logging, planned for 25 years after planting. The high survival rate of planted trees would help the regeneration of desired species and increase the productivity potential for longer-term management even if the forests were heavily harvested. Although it is necessary to deal with the cost problems, according to Ådjers et al. (1995), our results demonstrated the feasibility of achieving sustainable yields using a line-planting system.

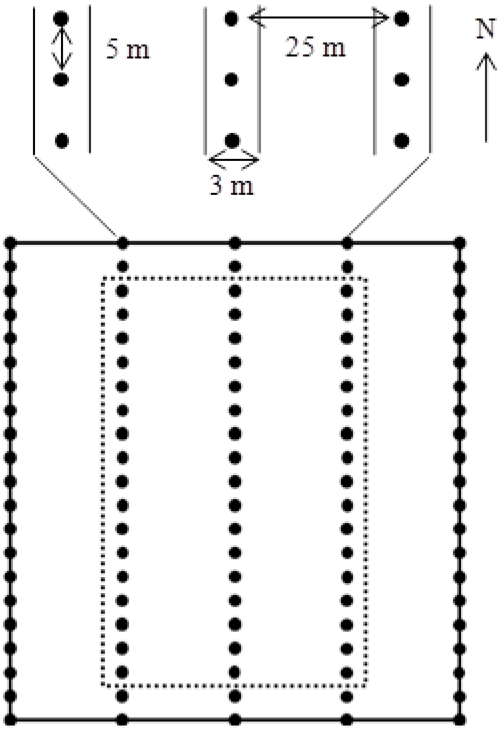

Fig. 5-1. Planting scheme in the 1-ha monitoring plot.
Dots represent the planted seedlings. Planted trees within the broken line were used in the evaluation of the crown illumination level using the three-dimensional model.

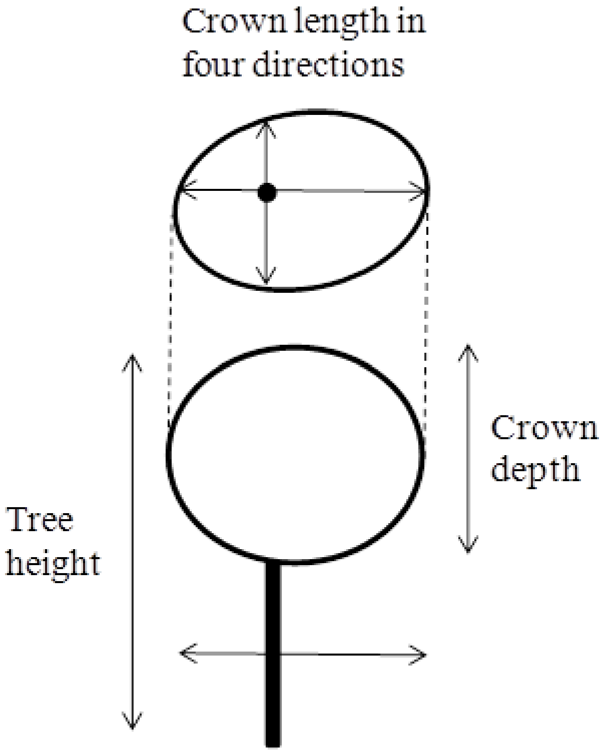

Fig. 5-2. Measurement of tree morphology.

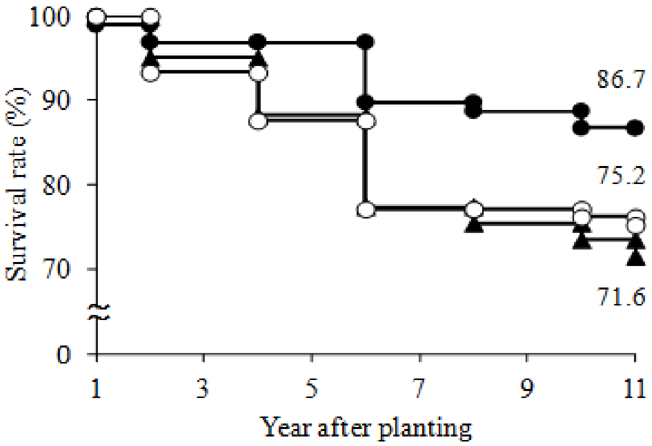

Fig. 5-3. Survival curve of planted *Shorea johorensis* for 11 years after planting in each three monitoring plots.

Blank circles, filled circles and filled triangles indicate the transitions of survival rate in the period during 1-11 years after planting in plot1, plot2 and plot3, respectively. Numbers express the survival rate in each monitoring plot 11 years after planting.

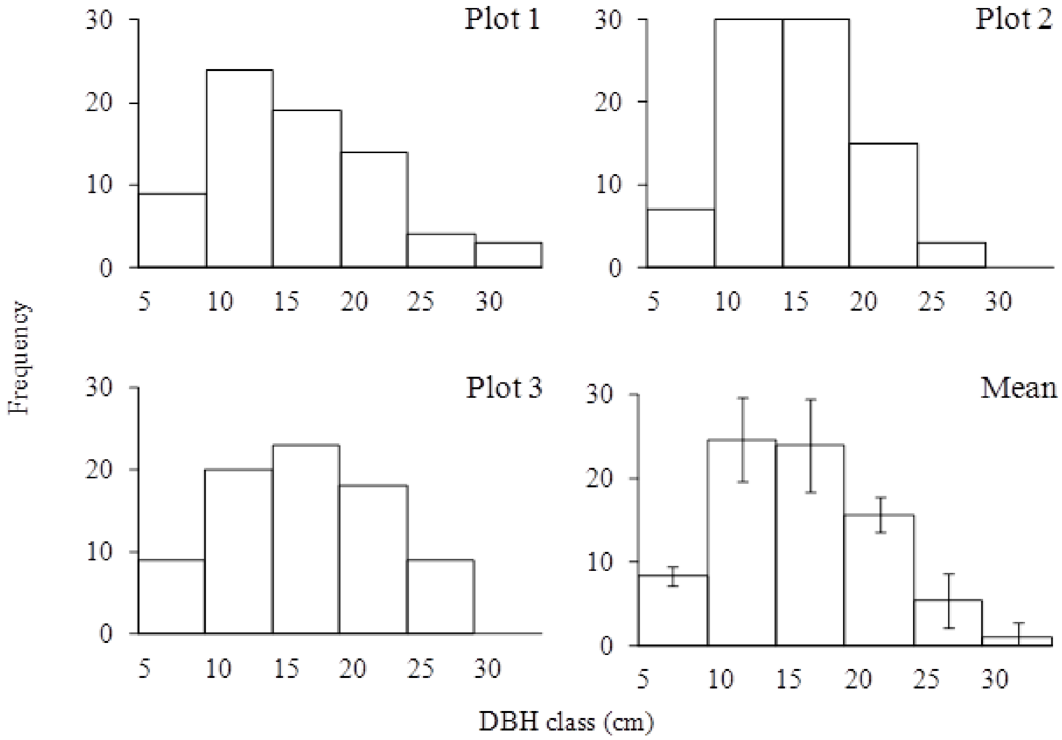

Fig. 5-4. DBH size distribution of *Shorea johorensis* planted in each monitoring plot and the mean of three plots.
Error bars indicate the S.D. among the three plots.

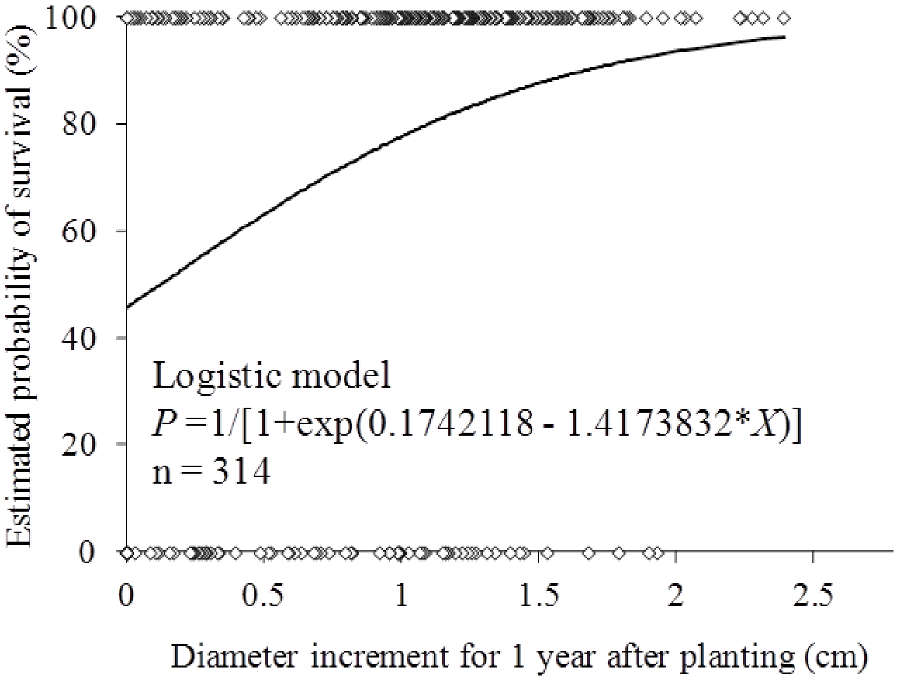

Fig. 5-5. Result of the logistic regression analysis of the probability of survival of planted trees at 11 years after planting. Thin line is regression model for the survival productivity. Blank square indicated the actual state of planted trees survive (100) or dead (0) 11 years after.

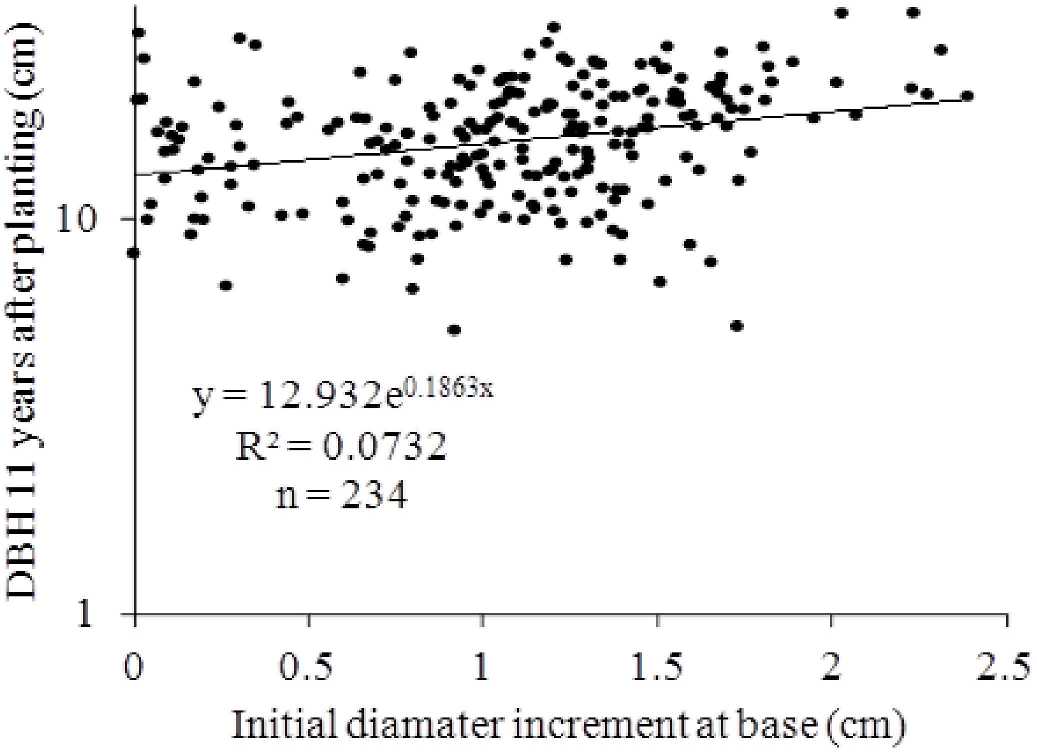

Fig. 5-6. Scatter diagram of the correlation between initial growth of diameter at base and DBH measured 11 years after planting for each planted *Shorea johorensis*.

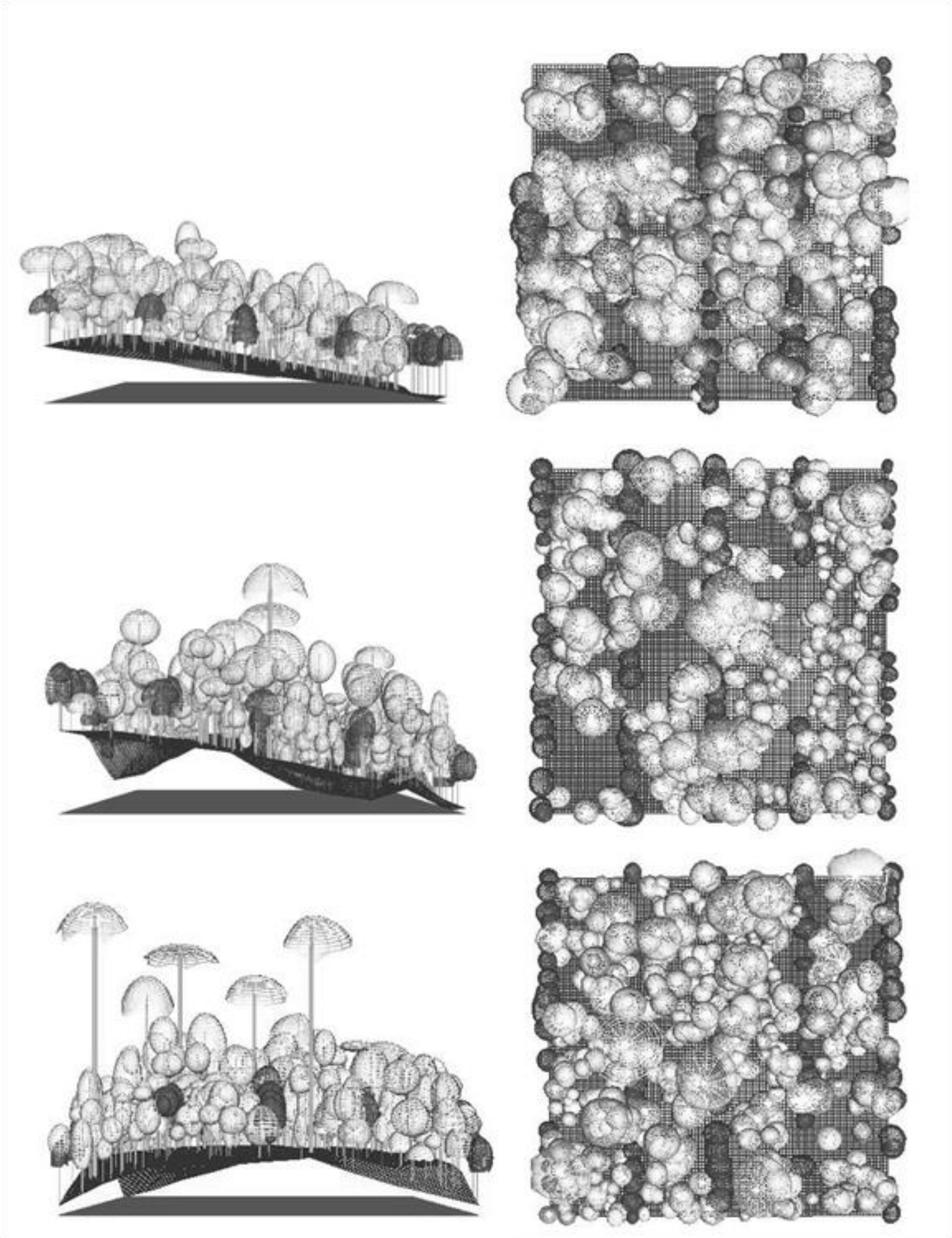

Fig. 5-7. Spatial structures of the three monitoring plots modeled using *SExI-FS*. Shaded crowns represent planted trees, white crowns all other trees.

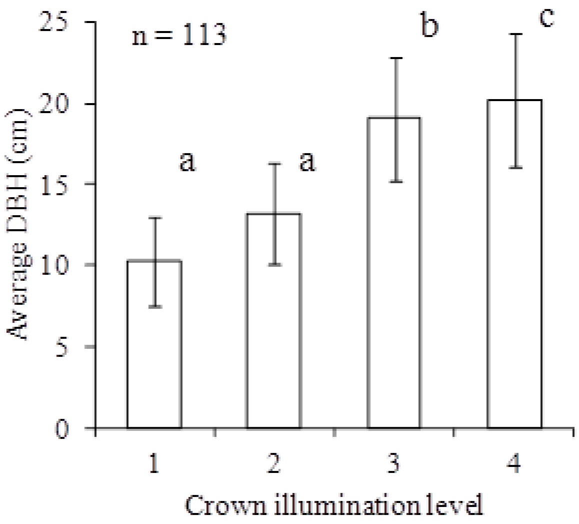

Fig. 5-8. Average DBH of planted trees in each crown illumination level. Error bars indicate standard deviations. Different letters indicate significant differences in average DBH as determined by *Steel-Dwass* test ($p < 0.05$).

Chapter 6 General discussion

Efficiency of the line planting system for sustainable management

The purpose of this study was to evaluate the sustainability of line planting system in lowland dipterocarp forest, in term of the efficiency for the regeneration of desirable *Shorea,* after logging to sustain the economical value of the forest.

As revealed in Chap. 3, the 10-years monitoring and comparison of post-logging dynamics under different logging management suggested the necessity of post-logging silvicultural treatment after logging. Conventional logging induced the damage to residual trees and significant pioneer invasion after logging. Pioneer recruitment and injury from logging decreased the residual tree growth and inhibit the regeneration of desirable species.

Reduced impact logging (RIL) functioned well for the mitigation of logging impact. Higher residual tree growth and suppression of pioneer invasion were found after RIL. However, the regeneration of meranti species did not promoted by RIL. The regeneration of meranti species was poor both in two logged-over forests by conventional logging and RIL. Only selective logging, even the logging impact was mitigated, the repeatable logging would deplete the economical value of forest and possibly induce the land conversion to other non-forest usage.

The feasibility for sustaining timber productivity by meranti was suggested in the well-tended logged-over forest stand. Under intensive management by removing competitor by annual slashing and changing light condition in forest floor by strip cutting for line planting, the natural regeneration of desiable *Shorea* was promoted significantly. Removing competitors to desiable *Shorea* species was considered to be efficient for the natural recruitment and the growth of planted trees. And line planting was effective to increase the potential productivity. Planted seedlings marked high survival rate and steady growth.

Under intensive management, the regeneration of desirable *Shorea* was promoted both by natural recruitment and planted seedlings. However, from the economical perspective, the enrichment planting such as the line planting treatment was costly. It takes high cost for the all the processes of line planting, establishment of nursery, growing the seedlings, strip cutting , and transplanting of seedlings.

To sustain the productivity, promoting the natural regeneration by removing competitors by slashing may be enough.

However, the regeneration by natural recruitment is depends on the regeneration ability by mother trees and seedling bank in post-logging forest. When the regeneration ability is poor, the slashing no longer be effective and some enrichment plating is recommended, and the line planting was proved to be the efficient way to reintorduce the desirable *Shorea* species in the forest in this study.

Further experimental studies to examine the cost-efficiency of the various combination of treatment will contribute to improve the current line-planting system.

For the improvement of the line planting system

In lowland dipterocarp forest, for the forest management, utilization of enrichment line planting treatment can be an efficient way to promote the reintroduce the meranti trees. However, from the long-term monitoring of planted trees, there was a large variance in the dbh size in a plating line (5.3 – 33.6 cm, 10 years after planting).

To improve the line planting system and enhance the feasibility of sustainable productivity, it is necessary to reveal the factors controlling the growth and survival of planted trees.

This study clarified the importance of light condition on the planted trees and monitor and assess the condition of planted trees in the forest stands line planting system installed (Chap. 4 & 5). From the hemispherical photography, the canopy openness fluctuated in a plating line. The pattern was similar to the variance in dbh size after 11-years monitoring (Chap. 5). From the monitoring of light condition change and planted seedling growth in initial 30 months after planting clarified the existence of the large initial variation in strip cutting line and it will continuously influenced the following growth of the planted seedlings. It was suggested that large canopy openness induced the pioneer invasion and it could suppressed the planted seedlings. In contrast, some planted seedlings were shaded from neighboring remnant trees along the strip cutting lines. In the planted lines, the neighboring trees along the planting lines affected to the light condition of planted seedlings.

The difference in the light condition of planted trees was also found from the three dimensional model in the 11-yr stand after line planting treatment (Chap. 5). Some trees were shaded by the neighboring trees and they were statistically smaller compared with the planted trees exposed to vertical sunlight, and the mortality was higher in the smaller size trees. Among the planted trees in 5-m intervals, the crown competition was not detected from the three dimensional model. At least 11 years after planting, it was not necessary for thinning for the planted trees.

For the planted trees in the plating lines, the initial light condition could affect to the long-term survival and growth. Even under same 3-m strip cutting treatment, the neighboring trees along the planting lines casts the shade to planted seedlings and influenced the their growth and induce the mortality caused by growth suppression.

Thus, for planted trees, the interaction with remnant neighboring trees was very important. Liberation from suppression from neighboring tree was expected to promote the growth and increase the survival rate of planted trees. However the liberation treatment will associate with further disturbance to the forest canopy and the impact of the treatment must be examined.

In recent scheme for line planting system, strip cutting treatment intended the enhancement of the light condition of planted trees functioned well. However, systematic strip cutting treatment sometimes no meaning for enhancing the light condition because of the heterogeneity of abundance and distribution of neighboring trees. For enrichment planting, the preparation for the planting, such as strip cutting treatment in line planting system is one of the factor of high cost. For the systematic line planting system, considering and reducing of strip cutting treatment would makes the management more cost-efficient. The evaluation of economical feasibility of line planting will be made in next harvesting. Line planting was obviously efficient to increase the stock of desirable species. The potential harvestable trees are expected to sustain the productivity in long-term managements after next harvesting.

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