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Neighboring tree effect on the survival and growth of *Shorea johorensis* under a line planting system in a Bornean dipterocarp forest

Tomoya Inada, Kaoru Kitajima, Mamoru Kanzaki, Widiyatno Ano, Suryo Hardiwitono, Ronggo Sadono, Priyo Eko Setyanto and Saminto

1 Graduate School of Agriculture, Kyoto University, Kyoto, 606–8502, Japan
2 Faculty of Forestry, Gadjah Mada University, Bulaksumur, Yogyakarta, 55281, Indonesia
3 Sari Bumi Kusuma Co., Ltd., Katingan and Seruyan block, Palangkaraya, 73111, Central Kalimantan, Indonesia

* Corresponding author: tinada1020@gmail.com

ABSTRACT In Indonesia, in recent years, line planting of valuable *Shorea* species has taken place on logged forest to maintain the timber yield. However, there exists scant information about the effectiveness of such a method. Neighboring trees along the planting lines affect the planted trees. We assessed the survival, growth, and crown exposure of the planted trees to evaluate the effect of neighboring trees in three 1 ha-monitoring plots, in which *Shorea johorensis* seedlings had been planted at a 5-m spacing along five parallel lines separated by 25 m, all running in a north-south direction within a 3 m-wide strip. The planted trees were monitored for 11 years after planting. The crown exposure was evaluated using a three-dimensional spatial structure model and 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, ranging widely from 5.3 to 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 subsequent growth rates. The variation in light conditions in the planting lines affects the growth and survival. The spatial structure model illustrated how neighboring tree crowns suppress the growth of the planted tree by casting shade. In a line-planting system, the neighboring tree effect influences the survival and growth of the planted trees, and this can be reduced by treatment of the canopy to ensure exposure of planted trees to sunlight.

Key words: line planting, enrichment planting, *Shorea* species, lowland dipterocarp forest, light condition

INTRODUCTION

In Southeast Asia, the total forested area is decreasing at an alarming rate due to commercial logging (Ashton and Kettle 2012). In primary forests, the dominant family is Dipterocarpaceae, which includes the main commercial *Shorea* species, *Shorea johorensis*, *S. parvifolia*, *S. leprosula*, and others (Appanah and Weinland 1993). Selective logging targeting these *Shorea* species is a commonly employed system (Sist et al. 1998). Harvesting of the mother trees depletes the ability for regeneration and, after extensive logging disturbance, pioneer species often invade the logged forest and inhibit the regeneration of dipterocarps (Slik et al. 2002). The resultant secondary forests with low commercial values 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). Therefore, the sustainability of commercial selective logging of dipterocarps is the key to promoting the conservation of natural forests in Southeast Asia.

Enrichment planting has been used for sustainable management of forests lacking sufficient regeneration ability (Sovu et al. 2010). In Indonesia, in recent years, a logging system combining selective logging with enrichment line planting of the main commercial *Shorea* species has been adopted (Pamoengkas 2010). In this system, seedlings are planted in strips cut into selectively logged forests. The strips are employed to enhance the light conditions in which the *Shorea* seedlings are growing because of the considerable light demand of the Dipterocarpaceae (Clearwater et al. 1999; Phillips and Yasman 2002). Numerous previous studies report that some degree of canopy opening improves the growth of planted *Shorea* (Bebber et al. 2002; Kuusipalo et al. 1996; Hattori et al. 2013). However, information regarding the efficiency of the line-planting system for regeneration of timber trees is scarce. In previous studies of *Shorea johorensis*, one of the main commercial species, the survival rates of planted trees were 38–65% after 3 years (Matsune et al. 2006) and 55–73%, after 2 years (Adjers et
The growth and survival of the planted trees varied with planting direction and strip width (0–3 m). In open grassland, planted dipterocarp seedlings grew rapidly, although the high light intensity induced mortality. The survival rate decreased to about 20% at 2 years after planting (Hattori et al. 2013).

In the planted lines of the strips, there exists a large variance in the light conditions (Inada et al. 2013), which can influence the growth of each planted tree. The light conditions 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 neighboring trees (Pamoengkas et al. 2014), particularly in the initial years after planting. In other words, in the absence of neighboring trees, the planted seedlings may grow rapidly and reach the main canopy.

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 Moer 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. And it is also needed to evaluate the efficiency of planting scheme.

Thus, to evaluate the efficiency of the line-planted system, this study assessed the growth and survival of the planted trees in relation to the initial growth. Moreover, to assess the effects of neighboring trees, the crown condition of the planted trees was also evaluated from a three-dimensional model of the spatial structure of the forest.

MATERIAL AND METHOD

Study area and monitoring scheme

This study was conducted in a logging concession in Central Kalimantan, managed by Sari Bumi Kusuma Co., Ltd (147600 ha, approximately 400–600 m a.s.l., 00°36′–01°10′ S, 111°39′–112°25′ E, Fig. 1). The forest type was lowland dipterocarp forest (Whitmore, 1990). The study site

![Study site](image)
was a logging compartment where a line-planting system had been applied in 2000 (119 ha), which is different from the selectively logged forest (SL site) of Inada et al. (2013) where line-planting was conducted in 2011. The logging intensity was 9.3 trees/ha ≥40 cm DBH, with a total harvesting volume of 45.5 m³/ha. For the line planting, 3-m-wide parallel strips running in a north-south direction were cut at 25-m intervals after logging. The planted species was *S. johorensis*. This species has a considerable light demand (Clearwater et al. 1999), and for this and similar *Shorea* species, a moderate light intensity supplied by 2–3-m-wide strips is recommended (Ådjers et al. 1995). 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. 2). 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. 3). The tree-top height and crown depth were measured with a LaserAce Hypsometer. The crown width was measured using a mea-
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. 2).

**Statistical 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 m²/ha, respectively. Eleven years later, these had increased to 373 ± 0.1 trees/ha and 23.4 ± 3.4 m²/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 m²/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. 4).

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.
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and average DBH. In each monitoring plot, we found considerable variation in DBH (Fig. 5). The DBH of all planted *S. johorensis* 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. 6). 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. 7).
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 *SExl-FS* software (Fig. 8). 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
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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. 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 (Ådgers 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 m²/ha to 452 ± 38.0 trees/ha and 24.9 ± 3.5 m²/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. 2014).
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 change 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 Ádgers et al. (1995), our results demonstrated the feasibility of achieving sustainable yields using a line-planting system.

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