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Research article

Stand growth scenarios for jabon (*Anthocephalus cadamba* Miq.) plantation management in Indonesia

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Abstract

Stand growth and management scenarios were developed for four different site qualities and three different initial stand densities of jabon (*Anthocephalus cadamba* Miq.) plantations in Indonesia. The objective was to analyze the differences in growth and yield generated for each management scenario and to find the most suitable scenario for maximizing timber volume. The scenarios were simulated based on growth curves generated for tree diameter and height, based on measurement data from 144 plots over six sites in Indonesia. The results indicated that among the 12 combinations of site quality and stand density, the rotation periods varied from age 10 yr to 20 yr, and the final density varied between 220 trees/ha and 367 trees/ha. The mean annual increment of timber volume at the end of the rotations was 8.0–21.2 m^3/ha/yr, thus accumulating a total timber volume of 122.4–317.5 m^3/ha over the rotation. The most feasible options for thinning in terms of intensity, number of trees and timing varied depending on the site quality and stand density. The two most suitable scenarios for jabon were on high-quality sites with initial stand densities of 1,667 and 1,111 trees/ha; both with three thinnings (intensities of 30–60% removal of the number of trees) and rotation ages of 15 yr and 13 yr, respectively. These two scenarios yielded very similar values of timber volume extracted at the final regeneration cutting (176.5 m^3/ha and 180.4 m^3/ha) with mean annual volume increments of 21.2 m^3/ha/yr and 20.9 m^3/ha/yr, respectively.

Introduction

Jabon (*Anthocepahalus cadamba* Miq.), also known as ‘kadam’, is an important tropical species planted for timber production as well as for reforestation and afforestation and has been planted on some islands in Indonesia (Java, Kalimantan, Sumatra, Sulawesi, Sumbawa and Papua) since the 1930s (Martawijaya et al., 1989; Krisnawati et al., 2011). Information on the actual area of forest plantations by species is currently not available but Cossalter and Nair (2000) reported that jabon had been one of the main species planted in timber plantations and farmers had also been planting this species for a long time. Jabon is considered to be one of the important plantation species because of its fast growth, its ability to grow on a variety of soils, its favorable silvicultural characteristics and the absence of

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serious pests and diseases (Soerianegara and Lemmens, 1993; Mansur and Tuhateru, 2010; Krisnawati et al., 2011). Expansion of jabon plantations by smallholders has occurred in Indonesia, particularly in Java, Kalimantan and Sumatra (Rohadi et al., 2010; Kallio et al., 2011; Wijayanto and Hartoyo, 2013; Irawan and Purwanto, 2014; Seo et al., 2015), which potentially support the livelihoods of the smallholders involved in tree planting. Nair and Sumardi (2000) reported that in some parts of Java, jabon is commonly planted to replace poor teak plantations after clear cutting. Some communities have also commonly planted this species for diversifying production and utilizing fallow land by applying appropriate propagation techniques to support good stand growth, especially under rural environments (Irawan and Purwanto, 2014).

Naturally, jabon is a typical pioneer species that is often found in secondary forests along riverbanks and in the transitional zones between swampy, permanently flooded and periodically flooded areas, although large individual trees are sometimes found in primary rain forests and the species occurs at elevations from sea level up to 1,000 m (Martawijaya et al., 1989). The annual precipitation required for the species is in the range 1,500–5,000 mm while some trees may grow locally on much drier sites with as little as 200 mm annual rainfall, such as in South Sulawesi. In its natural habitat, the maximum temperature varies from 32°C to 42°C and the minimum temperature is from 3°C to 15.5°C. The suitable soil for this species includes deep, moist, alluvial types, with well-accelerated fertility (Soerianegara and Lemmens, 1993).

Jabon trees growing in natural forests can reach a total height of 45 m with a stem diameter at breast height of 100–160 cm (Soerianegara and Lemmens, 1993). The wood is lightweight; the heartwood is white with a yellow tinge darkening to creamy yellow on exposure, and not clearly differentiated from sapwood (Pika, 1981; Martawijaya et al., 1989). The wood is suitable for multiple end uses, such as plywood, particle board, veneer, light construction, pulp and paper, flooring, boxes and crates, packing cases, ceiling boards, carvings, matches, chopsticks and pencils (Pika, 1981; Soerianegara and Lemmens, 1993). Total timber yields from jabon plantations have been reported to be around 150–400 m^3/ha depending on the spacing and intensity of silvicultural management (Mansur, 2009). The wood price varies, depending on size and quality. Hendarto (2009) reported that the average price of 1 m^3 of jabon wood was about USD 75–100. The minimum diameter size accepted by the wood industry is commonly 20 cm; however, a lower diameter size as small as 15 cm is also acceptable in local markets. If the productivity and the quality of the stands can be improved (for example through silvicultural management), farmers or timber producers can market wood of required quality and obtain reasonable prices, and thus potentially improve their income (Scherr, 2004).

In spite of the economic and ecological importance of jabon as a potential plantation species, relatively little information is available on its growth and yield, which has hindered its effective management in plantations. A preliminary stand yield table for this species was constructed based on data from sample plots from several sites in Java (Lembaga Penelitian Hutan, 1972). Subsequently, the table was updated by Suharlan et al. (1993) by including additional plot measurements. These reports, however, did not provide the growth models necessary for predicting or projecting stand development and evaluating different plantation management options. Managing plantations requires decisions about the planting density, timing, number and intensity of thinning and rotation age (Clutter et al., 1983; Smith and Sturb, 1991) which all affect biological variables and hence the volume and value of the products. The current study evaluated stand growth scenarios aiming to produce high timber volumes from jabon plantations. The scenarios were simulated using growth projection models developed for this plantation species. The main purpose was to analyze the differences in growth and yield generated for each scenario and to determine which scenario was the most suitable based on the maximization of timber volume as the objective. The results will provide guidance for smallholders and timber producers to market more productive plantations and improve the yield and their livelihoods.

Materials and Methods

Data description

The data used in this study were obtained from measurements of jabon stands in Java and South Kalimantan, planted by either company or smallholder farmers. The data were collected from both permanent and temporary sample plots established on five sites in Java (Banyumas, Ciamis, Indramayu, Jember and Kediri). Additional inventory data were included that had been collected from temporary sample plots in Tanah Laut, South Kalimantan. The locations of these six sites are shown in Fig. 1.

In total, 144 sample plots distributed over the six sites were used in this study. The plots varied in size from 0.016 ha to 0.5 ha with initial planting spacings of 2 m × 2 m to 5m × 5m. In each plot, diameter at breast height (DBH), total tree height (H) and tree height up to the crown base (h) of the standing trees were measured at each measurement. In total, there were 266 plot measurements available with stand ages (A) between 1 yr and 19 yr. In addition, the plot data included records of dominant height (Hd), number of trees per ha (N), basal area per ha (G) and total volume of trees per ha (Vt). An average (constant) form factor (F) of 0.47, obtained from data of plantation-grown-jabon in Java (Krisnawati et al., 2011) was used to calculate the total volume of the trees in a plot. The use of the constant form factor in tree volume estimation, which relates the total volume with diameter and height together (Husch et al., 2003), ($V = \pi/40000D^2HF = 0.0000369D^2H$), was considered to be adequate since the plantation species being studied generally had good stem form, with the main bole usually straight and clear. The associated merchantable volume (Vm) could be obtained from the proportion of merchantable height (height up to the crown base) to the total tree height (78–88% of the total volume, with an average of 83%). A summary of the plot dataset obtained from the six sites is given in Table 1.

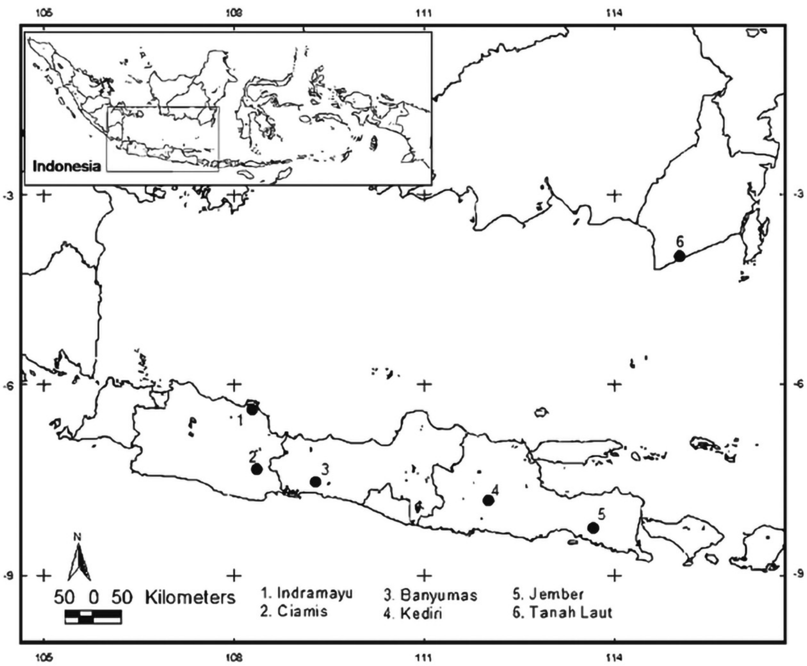

Fig. 1 Location of six sites where jabon plantation measurement data were collected in Indonesia

Table 1 Summary of plot dataset from six sites of jabon plantations

Site code*	Number of measurements	Elevation (m asl)	Stand age (y)	*N* (trees/ha)	*DBH* (cm)	*H* (m)	*G* (m2/ha)	*Vc* (m3/ha)
1	12	–	12.5–18.3	300–898	9.4–28.9	8.4–24.6	10.7–14.4	93.6–152.4
2	30	150	1.0–13.1	655–1558	4.8–25.1	3.8–24.3	2.7–9.2	4.8–91.4
3	38	100–200	1.0–16.3	530–1462	3.1–31.6	2.2–25.4	4.9–20.4	3.9–209.5
4	53	300–390	3.4–16.3	175–996	11.2–38.9	8.8–30.0	8.3–17.1	14.3–173.4
5	41	20–550	2.1–19.3	348–1416	7.2–36.4	5.3–25.8	4.7–20.2	9.2–218.3
6	92	5–40	3.0–5.0	360–1375	6.0–16.4	4.1–14.6	1.9–17.2	3.9–109.6

* 1 = Indramayu; 2 = Ciamis; 3 = Banyumas; 4 = Kediri; 5 = Jember; 6 = Tanah Laut; asl = above mean sea level; N = number of trees; DBH = diameter at breast height; H = total tree height; G = basal area; Vc = commercial volume.

Construction of growth models

Stand growth scenarios were constructed based on a set of growth models that had the ability to predict stand development over time. The first step was quantifying differences in site productivity (site quality). Site quality was determined by means of site index (*SI*), defined as the dominant height (*Hd*) of a stand at an index or base age (*Ab*) (Clutter et al., 1983; Avery and Burkhart, 2002). Several growth functions were tested to derive a polymorphic site index model assuming the growth rate was dependent on site, including the well-known Chapman-Richards function, the Schumacher function, the Lundqvist-Korf function and the McDill-Amateis function. These functions have also been previously tested in some studies for modelling site index and growth for plantations (Elfving and Kiviste, 1997; Amaro et al., 1998; Chen et al., 1998; Fontes et al., 2003; Palahí et al., 2004; Anta and Diéguez-Aranda, 2005; Carvalho and Parresol, 2005; Krisnawati et al., 2009).

The following model (Equation 1) derived from the Lundqvist-Korf function was found to be the best-suited site index model for jabon plantations:

$$SI = 35.65244 \left(\frac{Hd}{35.65244}\right)^{\left(\frac{A}{Ab}\right)^{0.52455}} \quad (1)$$

(root mean squared error (RMSE) = 1.34 and coefficient of determination (R^2) = 0.91)

The model is base-age invariant; however, a base age of 10 years was used to determine the site index of individual sample plots. Using the model (Equation 1), site index curves representing classes of dominant height at the index age could be generated.

Growth functions for mean diameter and height were developed using the relationships between the diameter at breast height (*DBH*) and stand age (*A*) as well as the total tree height (*H*) with age (*A*). Inclusion of stand variables such as site index (*SI*) and stand density

(N) was also examined but density was less significant and accounted for only little additional variation (<3%). In this case, site quality affected the mean diameter and mean height significantly more than density.

After testing and evaluating several functions, Equation 2 (derived from the Chapman-Richard function) was selected for modelling the mean diameter of jabon plantations:

$$DBH = 1.631305SI(1 - exp(-0.089888A))^{0.663579} \quad (2)$$

(RMSE = 1.36 and $R^2 = 0.86$)

The Chapman-Richard function was also found to describe the data well for predicting the mean height of jabon plantations (Equation 3):

$$H = 1.182173SI(1 - exp(-0.134517A))^{0.760687} \quad (3)$$

(RMSE = 0.97 and $R^2 = 0.97$)

Figs. 2A and 2B show the resultant growth curves of DBH and H used for developing the scenarios, respectively. Different growth scenarios representing different site quality classes (15 m, 18 m, 21 m and 24 m) were used, in which a higher site index represents a better quality of site.

Competition in the plantation was modelled as a function of the mean diameter (Equation 4), following the stand density index (SDI) relationship proposed by Reineke (1933) and also adopted elsewhere (Vacchiano et al., 2005; Zeide, 2005):

$$logN = -1.2507log(DBH) + 4.185216 \quad (4)$$

(RMSE = 0.11 and $R^2 = 0.78$)

This relationship was based on the concept of maximum number of trees possibly encountered in a stand and their negative correlation with the average diameter. This index could be used for determining intensity and age of thinning. The curve representing this relationship assumes a straight-line form when plotted on a logarithmic scale and is termed the ‘‘reference curve’’ (Reineke, 1933). The curves provide a good basis for understanding competition in even-aged forest or plantations (Lonsdale, 1990; Zeide, 2005).

All models developed in this study were selected based on evaluation of the model performance quantitatively and qualitatively, and by addressing both empirical and biological issues. The quantitative evaluation was based on statistical properties, such as asymptotic t-statistics for significance of the parameters, root mean squared error (RMSE), coefficient of determination (R^2) and residual plots to detect any obvious patterns of random errors. Other statistical measures as suggested by Vanclay and Skovsgaard (1997) and Huang et al. (2003) were also examined. The qualitative evaluation involved assessments of the consistency and correctness of the logical and biological aspects of the models such as value/sign of the parameter coefficients and quality of extrapolations outside data range.

Simulation of stand management options based on growth scenarios

Simulation of the stand management options was based on growth scenarios generated from the growth models, as described in the previous section. The scenarios were evaluated for the four different site quality classes (15 m, 18 m, 21 m and 24 m) and with three initial stand densities (625 trees/ha, 1,111 trees/ha and 1,667 trees/ha) representing wide (4 m × 4 m), intermediate (3 m × 3 m) and close (2 m × 3 m) initial planting spacings, respectively. These particular spacings were chosen since they have been commonly practiced by smallholder farmers and applied by most plantation companies growing jabon in Indonesia (Martawijaya et al., 1989; Soerianegara dan Lemmens, 1993), although farmers may choose a wider spacing of 5 m × 5 m in their jabon plantations by intercropping with fruit, food crops and rubber (Krisnawati et al., 2011). Other studies in teak plantations reported that farmers also plant timber at closer spacings (Kallio et al., 2012; Roshetko et al., 2013; Khasanah et al., 2015). Initial spacing was considered as this may affect both biological factors (plantation growth) and operational factors (silvicultural treatments such as thinning and regeneration cutting) (Smith and Strub, 1991). Separate simulations were made for each combination of site quality and initial stand density in which each resulted in different management options.

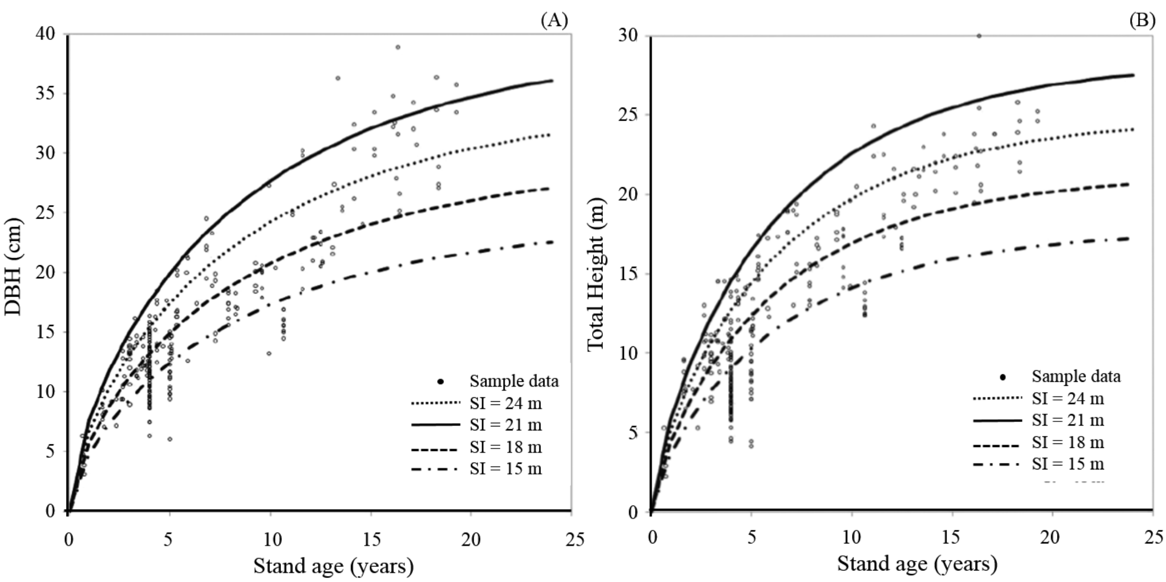

Fig. 2 Fitted models used in developing growth scenarios for jabon plantations: (A) relationship between diameter at breast height (DBH) and age; (B) relationship between total height and age, where SI = site index

A management option was first developed for no-thinning cases. Thinning was conducted to control the stand growth and yield by removing some selected trees. For options with thinning, the simulations were carried out as follows: (a) thinning was applied to keep the mean DBH after thinning equal to the mean DBH before thinning; (b) the first thinning could not be conducted until the stand was aged at least 2 yr; (c) the time between two thinnings, or between a thinning and the regeneration cutting could not be less than 2 yr to allow the stand to grow and recover from the thinning; and (d) a maximum basal area of 20 m^2/ha before thinning was applied as the upper thinning limit. For all simulations, a "thinning and regeneration cutting" option would be considered operable only if it met the two following threshold constraints: (1) each thinning or regeneration cutting had to yield a minimum of 20 m^3/ha of wood; and (2) the number of remaining trees after each thinning had to be at least 100 trees/ha. The first constraint was proposed to ensure that volume removed during the thinning and regeneration cutting would be economically sufficient. The second constraint was used to avoid problems associated with inadequate residual stand density to sustain a commercial plantation. Thinning intensities applied were between 20% and 60% of the number of standing trees removed. The upper bound of thinning intensity was set at 60% to avoid excessive opening up of the stand. The number of possible thinnings simulated in a rotation was zero, one, two and up to five thinnings.

Criteria used for determining the most suitable management scenario were the physical (volume) rather than economic (value) yield. In this study, the maximum possible rotation age was set to 20 yr so the results were comparable with the age range found in the dataset and in accordance with the rotation age recommended for jabon plantations managed by a state-owned company for producing timber (Perum Perhutani, 1995). A rotation age determined in this approach is often referred to as a physical rotation (Riitters et al., 1982; Clutter et al., 1983).

Results

Management options for timber production of jabon plantations were developed for four different site quality classes and three different initial stand densities (representing wide, intermediate and close initial planting spacing), resulting in 12 combinations of site quality and initial stand density. A summary of the most suitable scenario for each combination is presented in Table 2. The rotation lengths varied from 10 yr to 20 yr. At the end of rotation, stand densities varied from 220 trees/ha to 367 trees/ha, with a mean tree DBH of 20.0–32.1 cm and a mean total tree height of 15.9–25.5 m. The mean annual increment of timber (merchantable) volume at the end of the rotation varied from 8.0 m^3/ha/yr to 21.2 m^3/ha/yr, which accumulated a total timber volume of 122.4–317.5 m^3/ha over the rotation. These yields were feasible according to the field data.

Table 2 Summary of stand growth scenarios and management options for jabon plantations producing timber

Scenario (SI, spacing)	Stand age (yr)	Thinning number	Thinning intensity (%)	Number of trees (N/ha)	DBH (cm)	Total height (m)	Residual basal area (m^2/ha)	Removed basal area (m^2/ha)	Residual volume (m^3/ha)	Removed volume (m^3/ha)	Total volume (m^3/ha)
24m, 2m × 3m	2	1	60	667	11.8	9.5	7.3	11.0	27.0	40.5	40.5
	4	2	45	367	17.7	14.6	9.0	7.4	51.2	41.9	82.4
	8	3	40	220	25.1	20.7	10.9	7.3	88.0	58.7	141.0
	15	Final cut	100	0	32.1	25.5	0.0	17.8	0.0	176.5	317.5
24m, 3m × 3m	2	1	45	611	11.8	9.5	6.7	5.5	24.7	20.2	20.2
	4	2	40	367	17.7	14.6	9.0	6.0	51.2	34.1	54.4
	7	3	30	257	23.6	19.5	11.2	4.8	85.5	36.6	91.0
	13	Final cut	100	0	30.6	24.5	0.0	18.9	0.0	180.4	271.4
24m, 4m × 4m	3	1	50	313	15.0	12.3	5.5	5.5	26.5	26.5	26.5
	10	Final cut	100	0	27.7	22.6	0.0	18.8	0.0	165.4	192.0
21m, 2m × 3m	2	1	55	750	10.3	8.3	6.3	7.7	20.3	24.9	24.9
	5	2	45	413	17.5	14.4	9.9	8.1	55.5	45.4	70.3
	8	3	30	289	22.0	18.1	11.0	4.7	77.4	33.2	103.5
	16	Final cut	100	0	28.6	22.6	0.0	18.6	0.0	163.8	267.2
21m, 3m × 3m	3	1	50	556	13.2	10.7	7.5	7.5	31.6	31.6	31.6
	6	2	35	361	19.2	15.8	10.4	5.6	64.4	34.7	66.3
	9	3	30	253	23.2	19.0	10.7	4.6	78.8	33.8	100.1
	14	Final cut	100	0	27.4	21.9	0.0	15.0	0.0	127.7	227.8
21m, 4m × 4m	4	1	45	344	15.5	12.7	6.5	5.3	32.1	26.3	26.3
	12	Final cut	100	0	26.0	21.0	0.0	18.3	0.0	149.3	175.6

Table 2 Continued

Scenario (SI, spacing)	Stand age (yr)	Thinning number	Thinning intensity (%)	Number of trees (N/ha)	DBH (cm)	Total height (m)	Residual basal area (m^2/ha)	Removed basal area (m^2/ha)	Residual volume (m^3/ha)	Removed volume (m^3/ha)	Total volume (m^3/ha)
18m, 2m × 3m	3	1	55	733	11.3	10.7	7.3	9.3	30.7	39.0	39.0
	7	2	40	440	17.7	17.0	10.8	7.2	72.1	48.1	87.1
	12	3	30	308	22.3	21.0	12.0	5.1	98.3	42.1	129.2
	18	Final cut	100	0	25.4	23.1	0.0	15.6	0.0	140.4	269.6
18m, 3m × 3m	3	1	45	611	11.3	10.7	6.1	5.0	25.5	20.9	20.9
	8	2	40	367	18.9	18.1	10.2	6.8	72.2	48.1	69.0
	15	Final cut	100	0	24.1	22.3	0.0	16.7	0.0	144.7	213.8
18m, 4m × 4m	4	1	50	313	13.3	12.7	4.3	4.3	21.5	21.5	21.5
	13	Final cut	100	0	22.9	21.5	0.0	12.9	0.0	108.1	129.6
15m, 2m × 3m	4	1	55	750	11.1	9.1	7.2	8.8	25.6	31.2	31.2
	8	2	40	450	15.7	12.9	8.7	5.8	43.9	29.3	60.5
	13	3	25	338	19.1	15.3	9.7	3.2	57.9	20.1	80.6
	20	Final cut	100	0	21.7	16.8	0.0	12.5	0.0	80.7	161.4
15m, 3m × 3m	5	1	45	611	12.5	10.3	7.5	6.1	30.0	24.5	24.5
	10	2	40	367	17.3	14.1	8.6	5.7	47.4	31.6	56.1
	17	Final cut	100	0	20.8	16.3	0.0	12.5	0.0	79.5	135.6
15m, 4m × 4m	15	Final cut	100	0	20.0	15.9	0.0	19.7	0.0	122.4	122.4

SI = site index; DBH = diameter at breast height

Based on the scenarios (Table 2), the first thinning should be performed between stand ages of 2 yr and 5 yr depending on the site quality and spacing, except for the poorest site (*SI* = 15 m) with a wide spacing (4 m × 4 m), which did not need to be thinned over the rotation. The management scenarios with good quality sites (*SI* = 24 m) and intermediate to high initial stand densities (1,111–1,667 trees/ha) were considered to be intensive for jabon plantations with rotation ages of 13 yr and 15 yr. In these scenarios, three thinnings with intensities between 30% and 60% removal of the standing trees were applied. For high quality sites with high initial stand density, the basal area was reduced from 18.3 m^2/ha to 7.3 m^2/ha in the first thinning at age 2 yr, followed by two successive thinnings where 7.4 m^2/ha and 7.3 m^2/ha were removed from the stand at ages 4 yr and 8 yr, respectively (Table 3, Fig. 3A). In the final (regeneration) cutting of 220 trees/ha at a rotation age of 15 yr, the mean DBH was 32.1 cm and the mean total height 25.5 m. This final cutting would yield a timber volume of 176.5 m^3/ha with a total merchantable wood production (including thinning) amounting to 317.5 m^3/ha (Table 3, Fig. 3B). For high quality sites and for intermediate stand densities, the basal area was reduced from 12.2 m^2/ha to 6.7 m^2/ha in the first thinning at age 2 yr, followed by two successive thinnings where 6.0 m^2/ha and 4.8 m^2/ha were removed from the stand at ages 4 yr and 7 yr, respectively (Table 4, Fig. 3A). In the final cutting of 257 trees/ha at a rotation age of 13 yr, the mean DBH was 30.6 cm and the mean total height was 24.5 m yielding a timber volume of 180.4 m^3/ha with a total merchantable wood production (including thinning) amounting to 271.4 m^3/ha (Table 4, Fig. 3B). These two scenarios yielded very similar values of timber volume extracted at the regeneration cutting with mean annual volume increments of 21.2 m^3/ha/yr and 20.9 m^3/ha/yr, respectively.

Discussion

Jabon is one of the preferred species by smallholder farmers and forestry investment companies because of its fast growth, adaptability to a variety of sites, economic profitability and utilization variability. This study provided information on growth and management options for plantation managers or smallholder farmers or both to support the production of high timber yield from jabon plantations. The results indicated that for a jabon stand of a given planting spacing, the rotation length for timber production generally increased as the site quality decreased. Similarly, for a stand of a given site quality, an increase in the initial planting density increased the rotation age. These results were expected because the better site and lower initial planting density tended to produce larger timber sizes more quickly than a combination of poorer site and higher initial stand density, which encourage applying shorter rotations.

Thinning is usually practiced to remove inferior trees and to allow crown development which result in bole diameter increment. Thinning in jabon plantations can be done easily as the trees have straight stems and very regular small crowns. The first thinning should be performed between ages 2 yr and 5 yr depending on the site quality and spacing. At the time of the first thinning, the stands reached a mean total height of 8.3–12.7 m, which may be the time for thinning jabon plantations before the stands experience severe inter-tree competition and overcrowding; while concurrently, the trees are small enough to permit thinning with relatively light equipment to keep the thinning operation commercially viable. This result was in agreement with Martawijaya et al. (1989) and Soerianegara and Lemmens (1993) who considered that the first thinning in jabon plantations should be conducted early after canopy closure at about age 2–4 yr. Early thinning (at age 2 yr) is required to increase the proportion of merchantable stems in the final cutting, especially in dense stands and on good sites where residual growth potential is high. If the first thinning occurs at an older age (for example at age 5 yr and later), the potential yield for a given crop-tree density will probably not be achieved because of earlier losses due to growth stagnation. Average diameter responses are usually more pronounced when the first thinning occurs early in stand development (Nyland, 2002). In general, as site quality decreases, the best time for the first thinning increases. On the poor site, the first thinning was delayed 1–2 yr later than on moderate to good sites.

Table 3 Stand growth scenario for jabon plantations on high quality site (SI = 24 m) and high initial stand density (1,667 trees/ha)

Stand age (yr)	Thinning intensity (%)	Number of trees (N/ha)	DBH (cm)	Total height (m)	Residual basal area (m^2/ha)	Removed basal area (m^2/ha)	Residual volume (m^3/ha)	Removed volume (m^3/ha)	Total volume (m^3/ha)
1		1667	7.7	5.9	7.7		17.7		17.7
2		1667	11.8	9.5	18.3		67.5		67.5
1st thinning	60					11.0		40.5	
2		667	11.8	9.5	7.3		27.0		67.5
3		667	15.0	12.3	11.8		56.6		97.1
4		667	17.7	14.6	16.4		93.1		133.6
2nd thinning	45					7.4		41.9	
4		367	17.7	14.6	9.0		51.2		133.6
5		367	19.9	16.5	11.5		73.7		156.1
6		367	21.9	18.1	13.8		97.6		180.0
7		367	23.6	19.5	16.1		122.1		204.5
8		367	25.1	20.7	18.2		146.6		229.0
3rd thinning	40					7.3		58.7	
8		220	25.1	20.7	10.9		88.0		229.0
9		220	26.5	21.7	12.1		102.4		243.5
10		220	27.7	22.6	13.2		116.5		257.5
11		220	28.8	23.3	14.3		129.9		270.9
12		220	29.7	24.0	15.3		142.6		283.7
13		220	30.6	24.5	16.2		154.7		295.7
14		220	31.4	25.0	17.0		165.9		307.0
15		220	32.1	25.5	17.8		176.5		317.5
Final cut									
15	100	0	32.1	25.5	0.0	17.8	0.0	176.5	

DBH = diameter at breast height.

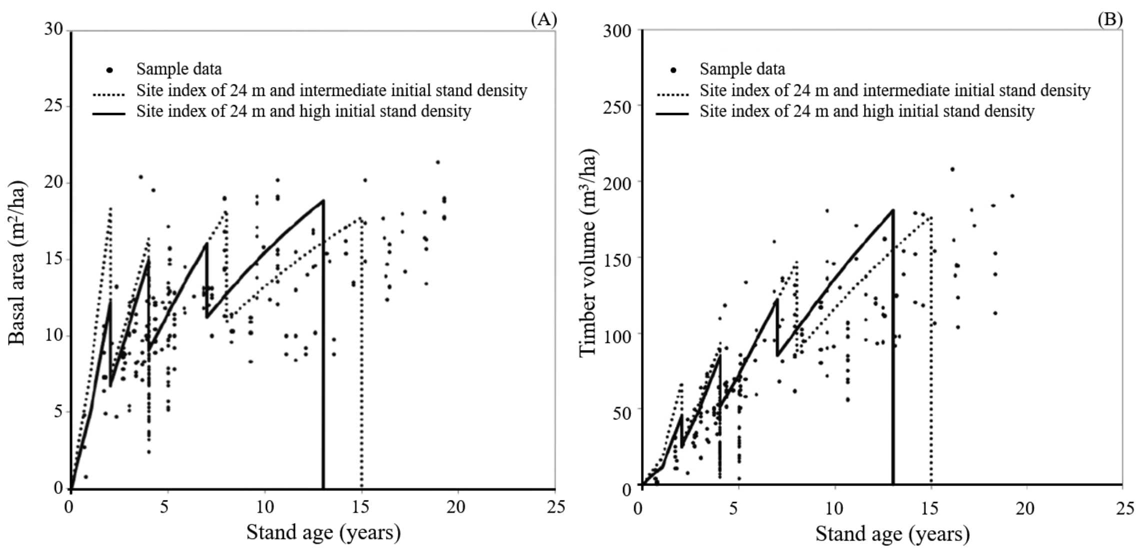

Fig. 3 Management scenarios for jabon plantations for site index of 24 m with intermediate and high initial stand densities (1111 and 1667 trees/ha): (A) stand basal area; (B) timber volume

Table 4 Stand growth scenario for jabon plantations on high quality site (SI = 24 m) and intermediate initial stand density (1,111 trees/ha)

Stand age (yr)	Thinning intensity (%)	Number of trees (N/ha)	DBH (cm)	Total height (m)	Residual basal area (m^2/ha)	Removed basal area (m^2/ha)	Residual volume (m^3/ha)	Removed volume (m^3/ha)	Total volume (m^3/ha)
1		1111	7.7	5.9	5.2		11.8		11.8
2		1111	11.8	9.5	12.2		45.0		45.0
1st thinning	45					5.5		20.2	
2		611	11.8	9.5	6.7		24.7		45.0
3		611	15.0	12.3	10.8		51.9		72.1
4		611	17.7	14.6	15.0		85.3		105.6
2nd thinning	40					6.0		34.1	
4		367	17.7	14.6	9.0		51.2		105.6
5		367	19.9	16.5	11.5		73.7		128.1
6		367	21.9	18.1	13.8		97.6		152.0
7		367	23.6	19.5	16.1		122.1		176.5
3rd thinning	30					4.8		36.6	
7		257	23.6	19.5	11.2		85.5		176.5
8		257	25.1	20.7	12.7		102.7		193.7
9		257	26.5	21.7	14.1		119.5		210.5
10		257	27.7	22.6	15.4		135.9		226.9
11		257	28.8	23.3	16.7		151.5		242.5
12		257	29.7	24.0	17.8		166.4		257.4
13		257	30.6	24.5	18.9		180.4		271.4
Final cut									
13	100	0	30.6	24.5	0.0	18.9	0.0	180.4	

DBH = diameter at breast height

The feasible number of thinnings varied depending on the initial planting density, ranging from one to three thinnings in a rotation. In stands with a close spacing, three thinnings in a rotation were sufficient to obtain a high timber yield at the end of the rotation. For stands with an intermediate initial planting, two-to-three thinnings appeared to be essential for obtaining high timber volumes; and one thinning option was generally suitable for wide spacings, except for the poorest site. For the low density stand on the poorest sites, no thinning was needed over a rotation length of 15 yr. At this age, the stand could reach a mean DBH of 20.0 cm, which is an acceptable size for sawn timber (the minimum size accepted by the local market is commonly 15 cm). Some of the smallholder farmers are reluctant to thin, and they prefer planting at low densities and applying the no-thinning option, as they gain other benefits by combining the jabon plantations with agricultural crops (such as agroforestry system, livestock grazing) (Kallio et al., 2011). Furthermore, conducting thinning in this stand can lead to longer rotations, and the volume yielded from the thinning operation would be low (below the defined threshold) and not sufficient for a commercial cut. Additional thinnings in the denser stands seemed to increase the timber volume over the rotation by cutting more of the trees that would otherwise have stopped growing earlier.

In the cases where two or three thinnings are recommended, the thinnings are separated by 2–5 yr. This period was considered to be sufficient for the trees to grow or recover from thinning and to reach the desired timber sizes. If the second or third thinning is postponed, the growth response may be slower, resulting in lower timber volume. Suharlan et al. (1993) proposed 3-yearly thinnings for jabon plantations growing on all site quality classes starting at age 3 yr until the end of rotation. However, according to the current study, such a management scenario is not recommended, because it resulted in too many light thinnings, which would be economically unfeasible to carry out.

The most appropriate intensity of thinning also varied depending on the initial planting density and site class. The intensity of thinnings ranged from 25% to 60% removal of trees in the stand. The thinning intensity was highest in the first thinning, decreasing for the subsequent thinnings. For stands of high density, a higher intensity of thinning (> 50% of the trees removed in the first thinning and then reduced gradually in subsequent thinnings) was generally suitable, whereas for intermediate initial stand densities, the suitable thinning intensity was about 30–55% removal of trees. This trend was expected for a shade-intolerant species like jabon, which is responsive to extra growing space and has crowns that are light-demanding (Martawijaya et al., 1989; Soerianegara and Lemmens, 1993). Thinning therefore accelerates most timber production when it is conducted at a relatively high density, in young stands soon after crown closure, and when crowns are still vigorous. However, it should be noted that applying light thinning (< 25%) in the simulation showed little effect on timber volume in stands with a high initial stand density.

The recommended rotation lengths also varied according to the initial planting density and site quality class, that is between 10 yr and 20 yr. This result was consistent with previous reports (Lembaga Penelitian Hutan, 1972; Suharlan et al., 1993), which predicted that jabon plantations would reach their maximum mean annual volume increment between 9 yr and 24 yr, depending on the site quality. In the state-owned plantations in Java, the economic rotation length for jabon plantations was also defined as around 20 yr (Perum Perhutani, 1995). The shortest rotation result in the current study (10 yr) was in agreement with the report of Soerianegara and Lemmens (1993), which suggested harvesting of jabon trees for wood production can start from approximately age 10 yr. In the current study, this was in scenarios with a wide initial spacing, on high quality sites, and with only one thinning conducted at age 3 yr (thinning intensity of 50% of trees removed). Multiple thinnings seemed to be suitable only in stands planted at closer initial spacings; the remaining trees after thinning may grow slowly to reach the desired size of timber and therefore require longer rotations (2–5 yr longer than for a wide spacing). Increasing the planting density generally increased the rotation age and increased the intensity and number of thinnings over the rotation.

From the three options of initial stand densities evaluated in the current study, the differences in the mean annual volume increment at the end of the rotation were not very large from the wide to the close spacings in almost all site quality classes. This indicated that stand density has a less pronounced effect on the total timber volume than site quality, and thus the choice of spacing among these three options would not cause a severe loss in volume at regeneration cutting. Close spacing may be more appropriate on good sites as they offer the greatest opportunity for maximizing total volume or for selecting the best trees for regeneration cutting. Wider spacing may be better on inferior sites. This could be an option for some of the smallholders willing to practice other activities (agroforestry, grazing) in their woodlots as well for those with little time and resources to conduct thinnings. However, if low survival becomes a problem on poor sites, the initial planting density should be high enough to ensure adequate stocking after early mortality. Intermediate initial spacing may provide a reasonable compromise between growth allocated to stand volume versus tree size.

The results from this study provide useful information on growth and yield prediction as well as on management options for jabon plantations in Indonesia. The information is also potentially useful for other areas with similar conditions, not only in Indonesia but also in other countries where jabon is planted. This may assist timber producers seeking to estimate growth in their jabon plantations and to guide plantation management. It should also help smallholder farmers and forest plantation managers who must decide which management scenario will best meet their objectives for growing jabon for timber production. This would have implications for smallholder livelihoods and hopefully for more feasible reforestation efforts. The management options resulting from this study could be applicable to other species under smallholder management. Further research on the techniques used for silvicultural management may help improve the quality of the stand.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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