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Intercropping Short Rotation Timber Species with Teak: Enabling Smallholder Silviculture Practices

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Abstract: Community forest management for timber production requires short- and long-rotation companion species to fulfill the demands of the timber industry, improve farmer welfare and maintain environmental sustainability. Four species (*Falcataria moluccana*, *Neolamarckia cadamba*, *Acacia mangium* and *Gmelina arborea*) were tested as short-rotation timber crop companion species for teak (*Tectona grandis*) on dry-rocky soil in the Gunungkidul community forest. The selection of short-rotation timber species was based on growth performance and survival rate at the teak site. Two years after planting, the viability of *G. arborea* (87.3%) and *A. mangium* (78.2%) was significantly ($p < 0.05$) higher than that of *N. cadamba* (40.6%) and *F. moluccana* (18.0%). *G. arborea* and *N. cadamba* achieved the best growth in terms of height, diameter, basal area, and volume, with the growth of *A. mangium* and *F. moluccana* being significantly inferior. *Gmelina arborea* has the ability to adapt to teak sites, grow well, and accompany teak. *Neolamarckia cadamba* demonstrated good growth with potential as a teak companion, and it demonstrated limited drought tolerance on the dry-rocky soils of the study sites. *Acacia mangium* had a high survival but produced slow growth, indicating that it required an advance evaluation in future years. *Falcataria moluccana* has different growing site requirements to teak so the performance was relatively poor at the study site. This mixed pattern provides benefits to farmers through commercial thinning of short rotations species, 5–8 years post establishment. Thinning operations will also increase the productivity of residual teak stands. The diversification of timber species in community forests can provide earlier returns, enabling the adoption of silviculture management by smallholders and communities.

Keywords: short rotation timber; teak mixtures; community forest; commercial thinning

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1. Introduction

Community forest development can be a solution to overcoming the supply and demand imbalance of raw materials of the wood industry. Timber trees produced on-farm (by smallholders) are able to efficiently supply timber products for household needs in local and national markets [1–4]. This is an opportunity for a community forest and smallholder agroforestry systems to empower local economies and enhance the local environment, since planting trees improves land cover and produces timber and other tree products for market sale or home use, enhancing local livelihoods [5–7]. Integrating conservation, rehabilitation, and community-based management of natural resources have vital importance, not only to maintain livelihoods, but also to protect off-site (downstream, urban) ecosystems [8,9]. The use of a variety of tree species will improve ecosystems' resilience, promote biodiversity, amend soil conditions [10–12], and enhance system resistance to pests and diseases [13,14].

Inappropriate tree species selection often occurs when the ecological conditions of the target site are not properly considered [15]. This can lead to negative impacts [8], as illustrated by a peatland restoration effort that achieved less than 25% survival after five years when the site condition was not integrated into the species-selection criteria [16]. Species–site matching is particularly important when restoring or reforesting degraded soils [17]. Limited understanding regarding tree species, ecological interactions, and adaptability, and economic value may lead farmers to plant only one or a few species. Intensive monoculture systems of tree crops can deplete the soil nutrients, affecting long-term productivity [18], and are more vulnerable to pests and diseases [12,14]. Key criteria for species selection for community forest systems or any tree activity include that they be suitable and productive for site conditions, have good performance and productivity, high economic values (with accessible markets), and responsiveness to the intended level (high to low) of silvicultural management [19].

The tree species selected for any tree planting or community forestry program must be productive in a reasonable time span [20]. The intention should be to interplant multiple species that will provide products in the short-, medium-, and long terms. The purpose of selecting fast-growing tree species for community forests is to provide farmers with short-term income and encourage the adoption of silviculture management. In the Solomon Islands, the cultivation of the flueggea (*Flueggea flexuosa* Muell. Arg.) with teak was introduced to overcome the reluctance of farmers to thin their stands by providing economic returns to thinning operations [21]. Increasing the productivity and financial returns from teak cultivation through thinning and species diversification is an aim in many teak-producing countries [12]. Having multiple species that are productive, marketable, and match local planting sites is necessary to achieve such an aim [21,22].

Gunungkidul, Yogyakarta, in Central Java, is famous as a *T. grandis* (teak) production area, where the species dominates local tree production systems. *Tectona grandis* is a high-value timber species with a rotation age of 20–30 years [22–24]. Proactive silvicultural management, particularly thinning, will enhance system productivity, value, and financial returns [22,25]. Farmers and communities remain reluctant to thin their teak systems because they consider thinning a loss of future income [2,26]. It would be beneficial to have short-rotation timber crops as companion species in *T. grandis* systems, which would enable early thinning to yield commercial products [4,22]. Possible fast-growing short-rotation companion species include *Falcataria moluccana* (syn. *Paraserianthes falcataria*), *Neolamarckia cadamba* (syn. *Anthocephalus cadamba*), *Acacia mangium* and *Gmelina arborea*. The rotation of *F. moluccana* is six years [27,28]. Similarly, the rotation of *N. cadamba* is 5 to 6 years [29,30]. The optimum rotation of *A. mangium* and *G. arborea* is eight years [31–34]. The natural distribution of three of these species is predominantly in Southeast Asia; *F. moluccana* and *N. cadamba* are native to Indonesia [30,35], while *A. mangium* is native to Papua New Guinea and Australia [36,37], but is now common in Indonesia. *Gmelina arborea*, native to South Asia, is a priority species for the rehabilitation of critical lands and the development of timber plantations [38,39]. These four fast-growing species may have varied adaptability and potential as companion species for community forest conditions in Gunungkidul, Yogyakarta, Indonesia.

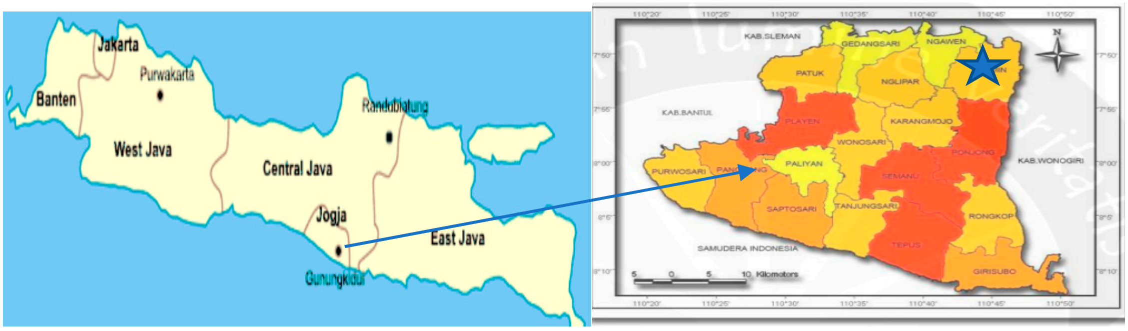
Most of the timber species that have found mixed successfully with teak have a rotation of more than 10 years (*Mitragyna parvifolia*, *Terminalia tomentosa*, *Anogeissus latifolia*, *Dalbergia sisso* in India [13], *Artocarpus hirsuta* in India [40], *Darbergia latifolia* in Indonesia [41]). Therefore, it is necessary to select fast-growing timber species for teak sites for commercial thinning in mixed plantings. The main purpose of this study was to evaluate suitable fast-growing short-rotation timber species as companion species for slower growing premium quality timber species *T. grandis* on rocky-dry soils in Gunungkidul. Mixed plantings have similar or higher productivities than monoculture planting [13]. However, species mixtures need to be rigorously tested at an experimental level before opting for large-scale plantations [13]. The specific objectives of the research study were to: (i) document the survival and growth of the four fast growing short-rotation timber species for sites in

Gunungkidul; (ii) inform species selection options for farmers regarding the four species; and (iii) evaluate the potential of the four species as companion crops for teak intercropping.

2. Materials and Methods

2.1. Site and Soil Characteristics

The research was conducted on dry-rocky land in a community forest in Gunung Kidul District, Yogyakarta Province. The area is governed by the Semin Village government, Semin Sub-District, Gunungkidul, Yogyakarta, Indonesia (Figure 1). The location has an elevation of 206 masl, average daily temperature of 26.65 °C, minimum temperature of 17.3–22.6 °C and maximum temperature of 32.2–35.5 °C. [42]. Relative humidity ranges between 68–85%. Rainfall is 1837 mm/year, with an average of 103 rainy days/year and a pronounced 6-month dry season when rain is less than 100 mm/month [43,44]. The dominant tree species in community forests in the study area is *T. grandis* [25,26].



(**a**) (**b**)

Figure 1. Map showing the location in Java (**a**) the specific study area in Gunungkidul, Yogyakarta (**b**).

Composite soil samples were collected in each experimental unit by taking five samples from a 20 cm depth at points along a diagonal line across the unit; soil from the 5 points was mixed, and a 1 kg subsample was taken for laboratory analysis to characterize chemical and physical soil properties [39]. Results indicated the soil in all blocks is a litosol [43], with components for sand, silt, and clay, low organic material, pH of 6, very low total N, very high K availability, and varied P_2O_5 availability. Litosol soils are formed from volcanic activity, specifically the weathering of igneous rocks and sediments. Litosols soils are suitable for secondary crops and perennials [43]. The soil surface is composed of limestone, generally suitable for teak [44]. In some spots, rocky limestone is exposed above the soil surface. Soil characteristics for each block in the trial are presented in Table 1. The soil at the research site has a shallow depth and is sensitive to erosion, resulting in low levels of organic matter. There were no apparent differences in teak silvicultural practices (by farmers) between the good and poor sites [45].

2.2. Germplasm Procurement, Trial Establishment and Trial Design

Research design, work execution agreements and ideas were carried out together openly and in a participatory manner with the farmer groups (research participatory). The submission process began with a Focus Group Discussion (FGD) with farmer groups at the research site. The results of the FGD were the determination of fast-growing timber species, determination of farmers' lands for planting, implementation of planting, maintenance and evaluation of measurements.

Table 1. Soil characteristics of the trial site in Gunungkidul District.

Site × Species	Soil Texture			pH (1:5)	C-Organic Material	N Total	K Available	P2O5 Potencial Available	Rocky Percentage	Slope
	Sand (%)	Dust (%)	Clay (%)	(1:5)	(%)	(%)	ppm	mg/100 g	(%)	(%)
B1P1	22	37	41	6.05	1.00 (l)	0.07 (vl)	138 (vh)	20 (l)	20 (vl)	0–5
B1P2	35	26	39	6.34	1.11 (l)	0.08 (vl)	169 (vh)	21 (m)		
B1P3	43	25	32	6.15	1.48 (l)	0.07 (vl)	108 (vh)	20 (l)		
B1P4	40	28	32	6.15	0.92 (vl)	0.06 (vl)	69 (vh)	20 (l)		
B2P1	52	27	21	6.11	1.1 (l)	0.06 (vl)	373 (vh)	32 (m)	30 (l)	5–10
B2P2	34	35	31	6.20	1.26 (l)	0.08 (vl)	354 (vh)	39 (m)		
B2P3	41	35	24	6.29	1.13 (l)	0.06 (vl)	263 (vh)	25 (m)		
B2P4	44	28	28	6.54	0.79 (vl)	0.07 (vl)	211 (vh	23 (m)		
B3P1	33	17	50	6.09	0.9 (vl)	0.07 (vl)	172 (vh)	28 (m)	20 (l)	0–5
B3P2	42	39	19	6.15	2.05 (m)	0.17 (l)	796 (vh)	39 (m)		
B3P3	40	39	21	5.87	1.52 (l)	0.1 (l)	383 (vh)	23 (m)		
B3P4	22	46	32	6.25	1.41 (l)	0.11 (l)	480 (vh)	30 (m)		
B4P1	30	43	27	6.15	1.39 (l)	0.09(vl)	627 (vh)	33 (m)	(90) (vh)	30%–50%
B4P2	18	45	37	6.13	2.06 (m)	0.09 (vl)	538 (vh)	26 (m)		
B4P3	21	38	41	6.18	1.15 (l)	0.09 (vl)	334 (vh)	30 (m)		
B4P4	30	38	32	5.85	1.14 (l)	0.08 (vl)	474 (vh)	29 (m)		
B5P1	17	39	44	6.21	1.16 (l)	0.09 (vl)	206 (vh)	58 (h)	(20) (vl)	0–5
B5P2	19	44	37	6.27	1.21 (l)	0.1 (l)	226 (vh)	69 (vh)		
B5P4	22	37	41	6.57	1.41 (l)	0.09 (vl)	409 (vh)	54 (h)		

Remarks: B1, B2, B3 and B4 (Block 1, Block 2, Block 3 and Block 4), P1, P2, P3, and P4. Species 1 (*F. moluccana*), Species 2 (*N. cadamba*), Species 3 (*G. arborea*) and Species 4 (*A. mangium*). l (low); m (medium); vl (very low); h (high) and vh (very high).

The seeds of *G. arborea*, *N. cadamba* and *A. mangium* were collected from a community forest in Ponorogo East Java and seeds of *F. moluccana* were collected in Wonosobo and Purworejo, Central Java. These areas are primary seed collection areas for reforestation and restoration species in Indonesia [3], indicting the germplasm used in the study is representative of the genetic resources used in national reforestation activities. Seedlings of the four species were produced in a Gunungkidul and Purworejo nursery, operated by a farmer group and technicians according to standard nursery practices. The nursery soil media was a mixture of topsoil + cow manure (4:1). The nursery containers were 10 cm × 15 cm plastic polybags. Seeds were sown in media at a depth of ±1–3 cm. The seeds readily germinated. No insect or pest problems were encountered. Seedlings were maintained in the nursery for 4 months before field planting, at which time the seedlings of all four species averaged 34.8–66.6 cm with basal diameters of 0.3–0.5 cm. Field planting was conducted in December 2018. The research study was conducted for 2 years through December 2020.

Site preparation for the trial involved clearing of all weeds and shrubs using manual labor. This was followed by preparing planting holes of 30 × 30 × 30 cm, excavated manually at 2 m × 3 m spacings. As a basic fertilizer, 3 kg cow manure was applied per planting hole at the beginning of planting activity, based on recommendations for *F. moluccana* and teak [44,46,47]. Manure was mixed with top soil excavated from the planting hole then returned to the hole at the time of seedling planting. All trees were given additional fertilizer, 100 g of N:P:K (15:15:15) 12 months after planting. Top soil was mounded to a height of 5–10 cm around the base of each seedling (mounding). Weeding control was conducted every 6 months by slashing and weeding all vegetation with a 1-m radius of the seedlings. Replanting activities were not conducted. All sites received similar management based on the standard operational procedure.

The experiment design was a *randomized complete block design*, including all four species. The trial was replicated in 5 blocks. Each species unit consisted of 7 plants × 7 plants = 49 plants/species/block, with a total of 245 plants/species, and a total of 980 plants for all four species (Figure 2).

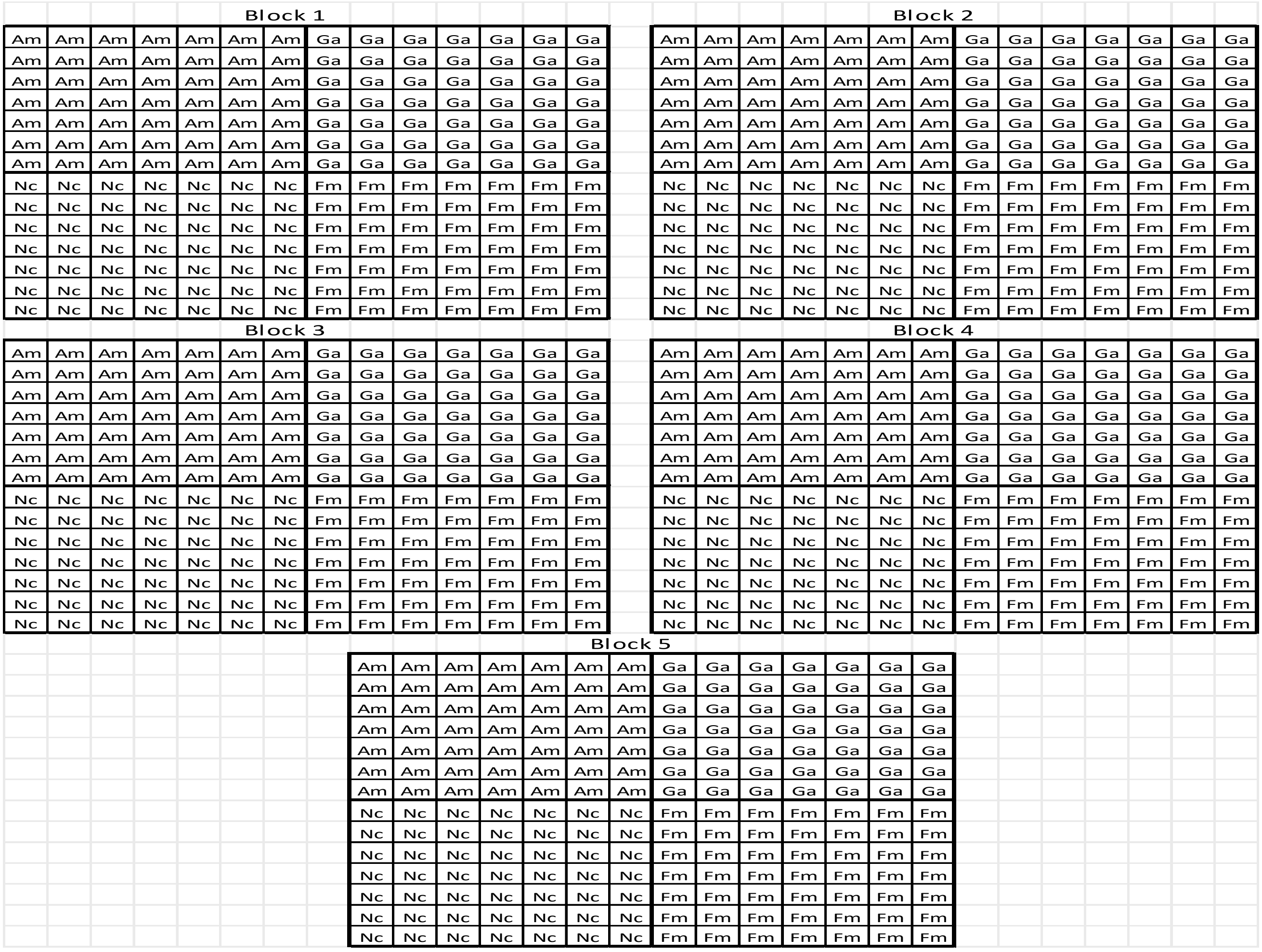


Figure 2. Experimental design of 4 fast tree growing species in community forests. (Fm: *Falcataria moluccana*; Ga: *Gmelina arborea*; Am: *Acacia mangium*; and Nc: *Neolamarckia cadamba*).

2.3. Data Collection and Analysis

Tree measurements were conducted every six months to collect data on seedling survival, height, and diameter. Canopy cover measurements were conducted when the trees reached the age of 2 years. A measuring pole was used to measure the tree height, from the soil surface to the tree's maximum height. A caliper was used to measure the tree diameter at near ground level (5 cm above the root neck). The survival rate (Sv) was calculated as the percentage of living trees. Basal area and crown diameter were calculated as follows [42]:

$$\text{Basal area } (\text{m}^2/\text{ha}) = \pi(\text{DBH}/2)^2 \quad (1)$$

$$\text{Crown area } (m^2) = \pi(\text{Crw}/2)^2 \quad (2)$$

where π = 3.146; DBH = diameter (m) and Crw = crown diameter (m).

Tree volume was calculated using the general formula viz.:

$$V = \frac{1}{4}\pi \times (D/100)^2 \times H \times f; \quad (3)$$

where V = tree volume (m^3); π = 3.146; D = diameter (cm) (±5 cm above the root neck); H = tree height (m); and f = form factor of 0.64 [48]

$$\text{Volume per ha } (V, m^3/ha) = \text{Vi. D0. Sv.} \quad (4)$$

where D0 = initial seedling density (n/ha) and Sv = survival rate.

After field collection, the data were analyzed descriptively and by analysis of variance (ANOVA) to determine the significance of treatments. Variance analysis using the F test was used to test the significance of variation between observed parameters. Duncan's multiple range test (DMRT) as a post-hoc test was applied when statistical analysis identified a significant treatment influence on the measured parameter [49,50]. ANOVA was performed on the crown area, height, diameter, survival/Sv, basal area, volume/tree and, volume/ha was determined using SPSS (Statistical Package for the Social Sciences) 20. The probability level used to determine significance was $p < 0.05$. The data and analyses were stored in the Kannopi2 project database.

3. Results

Based on the analysis of variance, there were significant ($p < 0.05$) differences in the survival, growth, and volume of 4 fast-growing tree species at 6, 12, 18, and 24 months of age (Table 2). This indicates that there is variation in suitability of the four tree species as potential companion species to teak at the study site. At 24 months after planting (MAP), *G. arborea* and *A. mangium* demonstrated good survival at 87.3% for *G. arborea* and 78.2% for *A. mangium*. The survival rate of both species was stable over the 24-month study period. Both *N. cadamba* and *F. moluccana* initially demonstrated good survival at 6 MAP, 84.1% and 67.2%, respectively. Unfortunately, the survival of both species decreased drastically after 6 MAP. At 24 MAP *N. cadamba* survival was 40.6% and survival of *F. moluccana* was 18.0%.

Table 2. Variance analysis on survival rate, height, diameter, basal area, crown area, and volume of the four fast growing tree species at 6 to 24 MAP.

Parameter	6 MAP		12 MAP		18 MAP		24 MAP	
	F-Value	Sig *p* Value	F-Value	Sig *p* Value	F-Value	Sig *p* Value	F-Value	Sig *p* Value
Survival	7.200	0.005 *	18.860	0.000 *	18.860	0.000 *	19.990	0.000 *
Height	74.560	0.000 *	33.880	0.000 *	48.200	0.000 *	30.990	0.000 *
Diameter	74.040	0.000 *	55.290	0.000 *	166.390	0.000 *	77.930	0.000 *
Crown area							34.700	0.000 *
BA/tree	26.284	0.000 *	43.064	0.000 *	103.212	0.001 *	47.360	0.000 *
BA/ha	6.8820	0.006 *	7.1890	0.005 *	11.166	0.001 *	5.459	0.013 *
Volume/tree	32.727	0.000 *	21.859	0.000 *	65.305	0.000 *	41.762	0.000 *
Volume/ha	7.138	0.005 *	7.159	0.005 *	8.823	0.002 *	3.838	0.039 *

Remark: BA = basal area; * indicates a significant difference at 5% level.

The best total height and diameter growth at 24 MAP was achieved by *G. arborea* (411.7 cm and 5.8 cm, respectively) and *N. cadamba* (372.1 cm and 5.5 cm, respectively). The total height and diameter growth at 24 MAP for *F. moluccana* was 349.1 cm and 3.9 cm, respectively; and for *A. mangium* it was 2.4 cm and 2.5 cm, respectively. The total height and diameter of *G. arborea* and *N. cadamba* was significantly greater than that of the other two species. Interestingly, at 12 MAP, the height of *N. cadamba* was less than that of the other three species. At 18 MAP, *N. cadamba* height growth equaled that of *F. moluccana* and *A. mangium*; at 24 MAP, its height exceeded both of these species. The species with the widest crown growth was *N. cadamba* (28.1 cm^2), which was significantly different ($p < 0.05$) from the other three species *F. moluccana* (18.8 cm^2), *G. arborea* (17.8 cm^2) and *A. mangium* (8.0 cm^2).

The largest basal area/tree was produced by *N. cadamba* (0.0031 m^2) and *G. arborea* (0.0030 m^2), which were not significantly different ($p > 0.05$) but were significantly different ($p < 0.05$) compared to *F. moluccana* (0.0011 m^2) and *A. mangium* (0.0007 m^2). In respect to basal area/ha, *G. arborea* achieved the greatest value (5.52 m^2/ha) followed by *N. cadamba* (2.61 m^2/ha), and there was no significant different ($p > 0.05$) between the two values. The superior tree survival of *G. arborea* enabled it to achieve a great basal area/ha compared to *N. cadamba*. The basal area/ha of *F. moluccana* was the smallest (0.42 m^2/ha) and was not significantly different ($p > 0.05$) to *A. mangium* (1.12 m^2).

The greatest volume/tree at 24 MAP was achieved by *G. arborea* (0.0098 m^3) although it was not significantly different ($p > 0.05$) than *N. cadamba* (0.0094 m^3). These data were significantly different ($p < 0.05$) with the volume/tree of *A. mangium* (0.0037 m^3) and *F. moluccana* (0.0018 m^3). *Gmelina arborea* and *N. cadamba* had similar values for the volume/tree parameter and the volume/ha parameter, with no significant difference ($p > 0.05$). Again, the difference was due to the great difference in survival rates of the two species (*G. arborea* 87.3% and *N. cadamba* 40.6%). Overall, the greatest stand volume/ha at 24 MAP was *G. arborea* (17.64 m^3/ha) followed by *N. cadamba* (7.86 m^3/ha). Stand volume/ha of *A. mangium* was (3.01 m^3/ha), and not significantly different to the smallest stand volume/ha of *F. moluccana* (1.38 m^3/ha).

4. Discussion

4.1. Smallholder Teak System in Gunungkidul, Yogyakarta

Teak is the dominant tree species in Gunungkidul community forests [22,23,26]. Smallholders cultivate teak in four systems: kitren (to producing teak timber), tegalan and pekarangan (tree and annual crops), and line planting (teak as border trees) [22]. Teak accounts for 56% of the trees in these systems and other timber species are an additional 21% [22]. Local teak is slow-growing, with smallholder teak systems described as overstocked, slow-growing, and of suboptimal quality and production [23].

The productivity and quality of these systems are low because the application of silviculture practices remains uncommon [26,51,52]. Smallholder farmers do not recognize the importance of proper silviculture management [53], resulting in few practicing silvicultural management [22,26]. Weeding and fertilizing of timber trees are only conducted when intercropping with annual crops (73% of farmers) [23]. Teak monocultures are generally not fertilized [52]. Most farmers (65%) prune their teak trees, but only to harvest fuelwood [22,23,53]. Farmers generally consider thinning an unprofitable practice [53]. Most teak systems in Gunungkidul (57%) are managed without thinning to increase growth and stand quality. The normal local practice is to "thinning" by harvesting the biggest timber trees and leaving the smaller trees [22,26]. Without thinning, with high density and low light intensity, teaks do not achieve their growth potential [54]. Most farmers do not develop a harvest plan according to the teak growth cycle. They harvest trees when they have an urgent need for cash [22,53]. The traditional harvesting system is called "tebang butuh" or "felling for need" [22]. In summary, smallholders harvest their trees when in need, rather than to achieve optimal financial returns [27].

4.2. Enabling Smallholder Silviculture Practices

Fast-growing timber species should be interplanted with teak by row—one row of teak, one row of fast-growing timber species, to accommodate farmers' needs for short-term income as well as their belief that thinning teak is unprofitable. Mixed plantations of teak and short-rotation timber species would make the first thinning a commercial operation, enhancing the growth of the residual teak stand and providing income for the tree grower [44]. In the teak monoculture, thinning is recommended when trees are 4–6 years old to reduce tree density (40–60% thinning intensity) [22,25,44,54,55]. In the mix row system, a 50% thinning could be conducted harvesting all the fast-growing timber species. Perum Perhutani, the state-owned forest enterprise, has trialed mixed plantations of 75% teak with 25% of *Acacia mangium*, *Eucalyptus pellita*, and *Melia azedarach*; of the three intercropped short-rotation timber species, only *Melia azedarach* failed [46]. In the Solomon Islands, mixed plantations by the row of teak and *Flueggea fexuosa* were established at densities of 833 stem/ha (4 m × 3 m). Harvesting of *Flueggea fexuosa* was conducted when the trees were five years old, providing income to landowners and improving the growth rate and value of the residual teak stand [56].

Intensive silviculture of mixed teak plantations can provide several benefits, (1) the fast-growing species provide short-term income, (2) pruning improves stem quality (and provides fuelwood), and (3) thinning improves the growth rate and quality of the residual stand [57]. Adopting these silvicultural practices would enable smallholder teak farmers to produce bigger, better quality teak more quickly than current practices. Intensive thinnings (+50%) had a positive effect on the stem form, inducing the development of trees with desired combination DBH and total height [54]. Clonal teak grows faster than common teak in the community forest. In clonal teak monocultures on Java, with an initial spacing of 6 m × 2 m, 50% thinning in year 4 yielded the best growth increment and standing stock three years after thinning (compared 25% thinning and no thinning) [44]. General recommendations for a teak system with a 30-year cycle is five thinning with 20–50% intensity at the age of 4, 8, 12, 18, and 24 years [54]. Thinning and pruning promoted positive DBH growth and an increase in the economic value of the residual stand and did not cause negative effects on the wood properties of the stems [54,55]. In clonal teak plantations in degraded soils, short-rotation commercial thinning could maintain growth rates and provide income for farmers [44]. This experience supports the application of mixed timber plantations (short rotation species with teak).

4.3. Early Growth of Four Fast-Growing Species as Companion Crops for Teak

4.3.1. Adaptability and Survival Rate of Four Fast-Growing Tree Species

In many countries, teak is grown on degraded lands that is partially poor in performance [51]. Over most of its range, teak occurs in moist and dry deciduous forests, below 1000-m elevation, with annual rainfall of 1250–3750 mm, minimum temperature of 13–17 °C and maximum temperature of 39–43 °C [12]. The physical environmental conditions at the study site are 1837 mm of rainfall, 6 dry months, temperature 17.3–35.5 °C and relative humidity 68–85%. This study site is slightly wetter than teak forests in two African countries, Togo (rainfall 1100–1400 mm, 8 months dry season, temperature 20–36 °C and relative humidity 83% [58]) and Ibadan Nigeria (1200 mm/year and 5 dry months [59]). However, this study site is slightly drier than teak forests in two American countries (Northwest) Costa Rica (rainfall 2231 mm, five dry moths, temperature 18.5–34.9 °C, relative humidity average 76%) [60] and teak forests in (Midwestern) Brazil (rainfall 2281 mm, 4 months dry winter, average temperature 25.4 °C) [61].

Survival rates of 65% are considered good for reforestation and rehabilitation activities [62]. This study found that *G. arborea* and *A. mangium* achieved 87.3% and 78.2% survival at 24 MAP, while *N. cadamba* and *F. moluccana* achieved survival rates of 40.6% and 18.0%, respectively (Figure 3). Usually, there is occasional rain during the 6-month dry season, even though it is below 100 mm/month. However, in the second half of the first year of this study, there was a five month period without a day of rain [63]. In the first

6 months of the study, all four species survived well. However, at 12 MAP, the survival of *F. moluccana* and *N. cadamba* declined drastically as a result of the 5-month drought. The impact of the drought on the four species was the desiccation of the foliage. Sensitivity to drought varies greatly by species [64,65]. While the other three species showed yellowing and drying leaves, the leaves of *G. arborea* remained green through the drought. Transpiration rate on tree's organ increases in concomitant with the increase of air temperature, causing a surge of vapor pressure on leaves [66]. Drought adaptation of deciduous species is to shed leaves. Species native to dry forests have a greater drought tolerance than species native to the humid forest, in general, 62 days to 25 days, respectively [65].

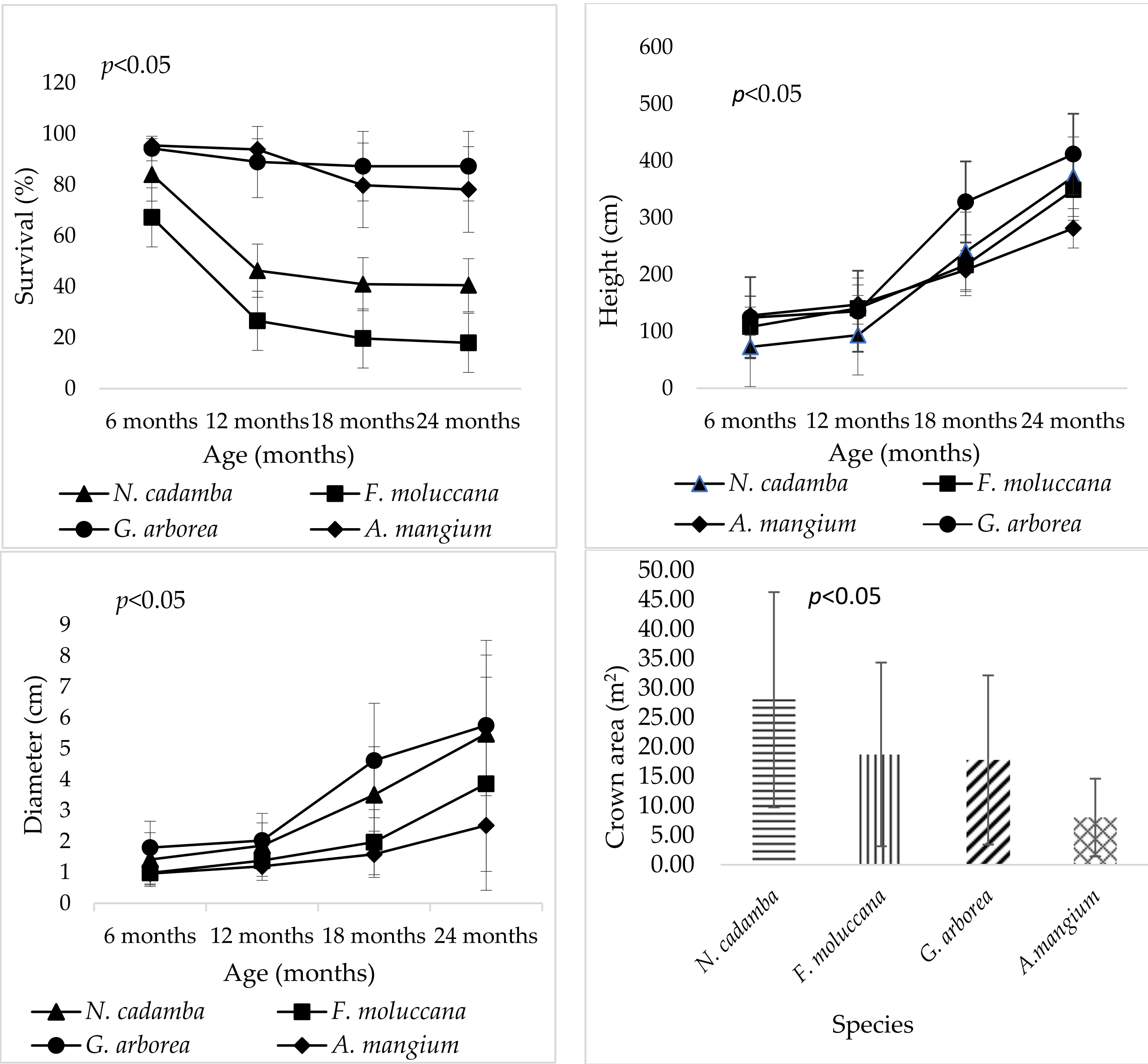


Figure 3. The survival rate and the growth of four fast growing tree species 24 MAP in rocky soil of community forest, Gunungkidul, Yogyakarta (data = mean ± SD, block = 5).

Other studies have reported *G. arborea* obtaining a high survival rate at rocky-dry sites in Gunungkidul [24]. *Gmelina arborea* is often grown with *T. grandis*, as they are in the family (Verbenaceae) [38] and are native to dry forest ecosystems. The requirements for *G. arborea* optimal growth are elevation of 0–800 m asl, rainfall 1.778–2.286 mm with the rainy season of 5–6 months [67], and maximum temperature to 35 °C [68]. *Gmelina arborea* was reported to perform well in Timor and Sumbawa with 99% and 100% survival, respectively, at 21 MAP [4]. Both locations share site characteristics that are similar to those of this study. *Gmelina arborea* demonstrates high survival on dry-land, but not on sandy soils, peatlands with tidal flows, or on impermeable soil with very thin solum layers [68–70]. The species survives on infertile soils but with slow growth [68]. In Garut, West Java *G. arborea* is tolerant to acid soils and sandy thin-solum soils provided the soil is well-drained [69].

Acacia mangium was proven to be the superior exotic tree for plantation in Indonesia [14]. It is fixing nitrogen and is high adaptability, robust, and tolerant of degraded infertile soils [71], including infertile acid soils, but does not survive on saline soils [37]. Native to humid ecosystems, *A. mangium* survives better under such conditions [18,72]. Under favored conditions in Malaysia, *A. mangium* demonstrated 66.6% survival at 18 MAP [73]. However, the species experiences high mortality under severe drought [37]. *Acacia mangium* is recommended as a suitable species for marginal land, such as degraded reed and grasslands [74].

Neolamarckia cadamba seedlings were more tolerant to waterlogging than drought stress [75]. The species requires more water to facilitate adequate nutrient uptake and translocation [45,76]. The survival of *N. cadamba* on drained peatland was reported as low (48%), with the species preferring dry-mineral soils [16]. In its natural range, the conditions for optimal growth of *N. cadamba* are temperatures of 32–42 °C, rainfall of 1500–5000 mm, and elevations of 300–800 masl (Table 3). The species cannot survive cold weather but grows on dry-land with an annual rainfall of at least 200 mm [16].

The result on the survival rate of *F. moluccana* in Gunungkidul showed the lowest percentage (18.0%) (Figure 3). In Sumbawa (7 dry months), the survival rate *F. moluccana* was found lower than *G arborea* [4]. The low survival of *F. moluccana* was caused by the first year's drought. At very dry sites, the growth of *F. moluccana* can be drastically reduced [35]. Its performance was worse under the no fertilizer control treatment. *Falcataria moluccana* is sensitive to site conditions, responding well to tillage and fertilization [77]. Adequate drainage is the main requirement for *F. moluccana* to grow well regardless of the soil type (dry soil, damp soil, high-salinity, acid soil) [78]. In another study in Gunungkidul, high mortality occurred in the first year after planting due to transplanting stress, low soil fertility, and lack of fertilizer application [79,80]. Optimum site requirements for *F. moluccana* growth are the temperature of 22–29 °C, wet climate with rainfall of 2000–2700 mm, and at least 15 rainy days during the dry season (Table 3) [35,78]. Sandy soil is more favorable to the growth of *F. moluccana*, yet its tolerance on various soil types [35,78]. Ideally, for *F. moluccana*, during dry months, there will be rain for at least 15 days [35].

4.3.2. Growth Comparison of Four-Fast Growing Tree Species at Other Sites

Overall, the best performance of the four species in this study was by *G. arborea*. The growth of *G. arborea* was greater than that of *N. cadamba*, but was not significantly better (Figures 3 and 4). However, its performance was significantly better ($p < 0.05$) compared to *A. mangium* and *F. moluccana* for all parameters (height, diameter, basal area/tree, basal area/ha, volume/tree, and total volume (Figures 3 and 4). In Hojancha, Costa Rica, in dry acid soil, the productivity and growth of *G. arborea* exceeded that of native species (*Terminalia amazonia*, *Vochysia ferruginea*, *Vochysia guatemalensis*, *Hieronyma alchorneoides*, *Calophyllum brasiliense* and *Schizolobium Paraiba*) [10]. The growth of *G. arborea* in this study resembles that at drier sites in Sumbawa, where height and diameter growth at 18 months were 425 cm/8.5 [81], and in Timor, where height and diameter were 240 cm and 4.6 cm, respectively, at 21 MAP [4].

Table 3. Requirement of physical environmental conditions for the growth of four species.

Characteristics of Site	Type of Soil	Elevation (masl)	Slope (%)	Soil pH	Rainfall (mm/year)	Dry Months	Temperature
Site trial	Litosol [43]	210 masl	0–50	5–6.5	1.837 [63]	6 [63]	17.3–35.5 °C [63]
G. arborea	clay loam soils [4] and Dust clay [68]	0–800 masl [68]	None	4–7 [68]	1.778–2.286 [68]	2–4 [68] or 6–7 [67]	Optimum 21–28 °C, Min. 18–26 °C, max. 24–35 °C [68]
N. cadamba	Moist alluvial soil [30] Various soil types with sufficient aeration [78]	300–800 masl [30]	None	4.5–8.5 [30]	1.500–5.000 [30]	19 °C–33 °C [30]	
A. mangium	Various soil types [37] laterite soil [77,80]	480–800 masl [37]	None	None	1.446–2.970 [37]	4 [37]	12–34 °C [37]
F. moluccana	latosols, andosols, aluvial and red-yellow podzolic soils. ref. [35] Solum 30–90 cm [78]	0 < 2000 and optimum 1600 [78]	8–15 [35]	4.5–7.5 [35]	2.000–3.500 [35]	>4 months (15 days rain/dry months) [35]	19–28 °C [1], 20–34 [10] and optimum 22 °C and 29 °C [78]

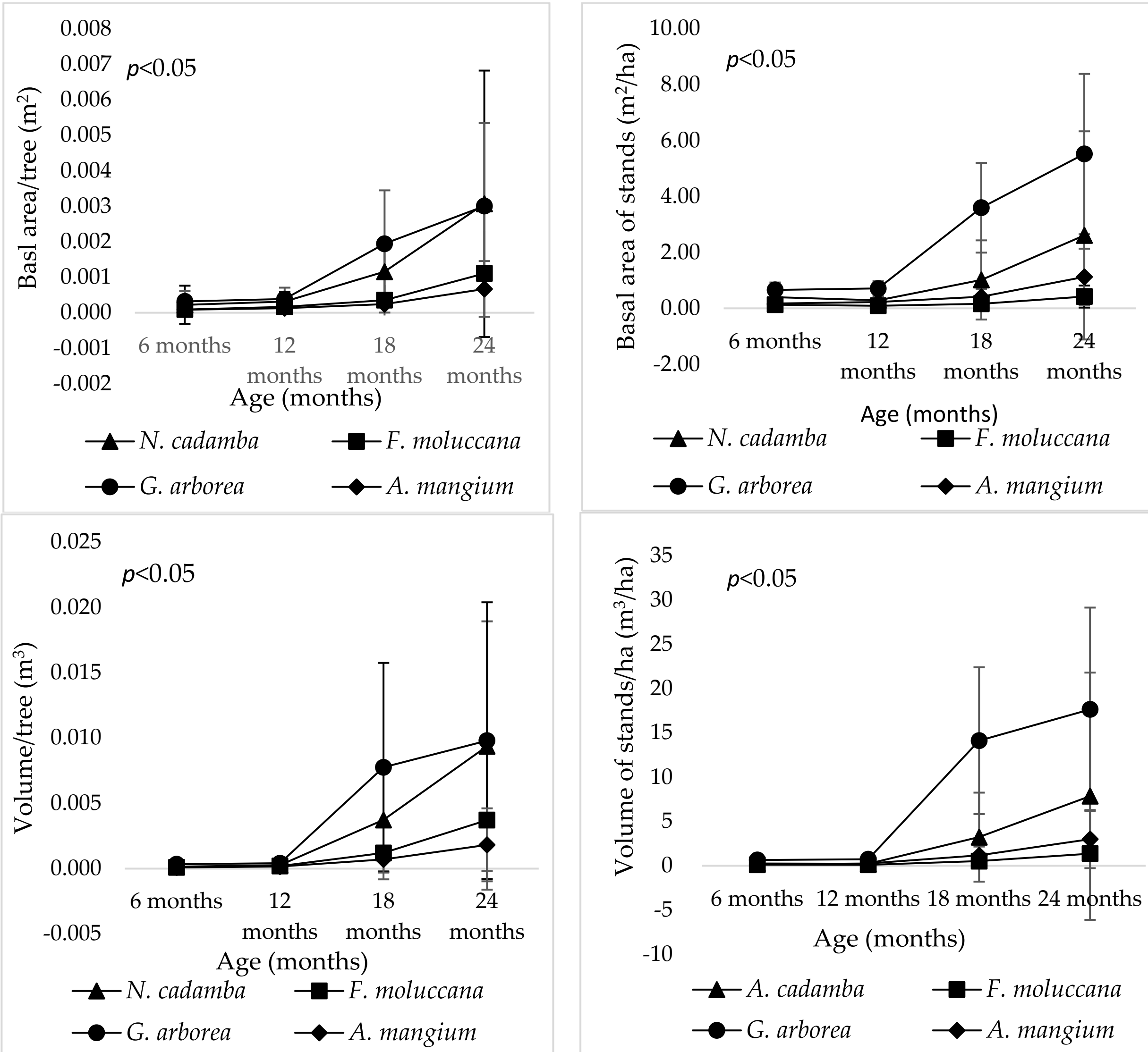


Figure 4. Basal area and volume of four fast growing tree species 24 MAP in rockydry soil of community forest, Gunungkidul, Yogyakarta (data = mean ± SD, block = 5).

Height and diameter growth of *N. cadamba* at 24 MAP in this study were comparatively better (372.1 cm and 5.5 cm, respectively) compared to growth in drained peatland in Riau (259 cm and 3.7 cm, respectively) at 24 MAP, and in plain peatland (417 cm and 5.2 cm) at 48 MAP [16,82]. The growth of *N. cadamba* in drained peatland was 401–660 cm in height at 24 MAP [16]. In a mineral soil in West Java, 10.5-year *N. cadamba* stands were reported to obtain an average height of 22 m (height increment 2.09 m/year) and an average diameter of 40.5 cm (diameter increment 3.86 cm/year) [78].

Acacia mangium is known to perform poorly under dry and drought conditions [30]. In this study, *A. mangium* survived and grew poorly due to low rainfall and drought (Figure 3). In a favored habitat in Malaysia, *A. mangium* has demonstrated height and diameter growth of 5.6 m and 6.8 cm, respectively, at 18 MAP [73]. The growth of *F. moluccana* was lower than that of the three other species (Figure 4). At a drier site in Sumbawa, *F. moluccana* achieved a growth of 498.9 cm in height and 6 cm in diameter at 21 MAP, double the values compared to this study [4,83]. *F. moluccana* grows well under a wide range of elevations, climatic conditions, and soil types [83]. It survives on rocky, reef, or coral-derived soils, but growth is not optimal [84]. Excellent growth is achieved on latosols, andosols, alluvial, and red–yellow podzolic soils [35,83].

Based on several studies at various sites, *G. arborea* shows variable height and diameter growth increments [14,31,39]. In this study, *G. arborea* revealed better performance compared to studies at three sites in West Java (Table 4). The difference in environmental conditions caused growth variations. The high soil fertility and rainfall in West Java do not necessarily generate better growth (Table 4). The growth increment of *G. arborea* tended to accelerate from 2–4 years of age through to 8–10 years of age [31,78,85,86], making it a suitable companion species for teak (Table 4). The growth of *N. cadamba* is generally better at dry sites compared to wet sites and peatlands [16,30,85–87]. The growth increment of *N. cadamba* at 24 MAP in this study was similar to those of dryland locations in Cianjur, West Java. The growth increment of *N. cadamba* increased about 4 years of age [29,85]. The growth of *F. moluccana* in this study was inferior compared to the growth in dry and sandy soils in West Java [47]. In this study, the growth of *A. mangium* was clearly less than those of studies in China, Malaysia, and West Java–Indonesia [14,73,88].

Table 4. Height and diameter growth of the 4 fast growing tree species in some trials.

No	Species	Height Growth (m/year)	Diameter Growth (cm/year)	Height (m)	Diameter (cm)	Age (Months; Year)	Location and Reference
1	*G. arborea*	2.05.	2.88	4.11	5.76	2 years	Trial site (Gunungkidul)
		1.25	1.42	187.33	3.467	18 months	Dry land, Ciamis, West Java [14]
		2.02–2.18	1.9–2.04	101.12–109.35	0.95–1.02	6 months	Dry land Trenggalek, East Java [89]
		1.43	1.21	11.47	9.7	8 years	Dry land Banjar dan Tasikmalaya (West Java) [31]
		1.00	2.7	10	24	10 years	Dry land, Gorontalo, North Sulawesi [90]
2	*N. cadamba*	1.86.	2.74	3.72.	5.48	2 years	Trial site (Gunungkidul)
		1.04	1.29	4.17 m	5.15	4 year	Peat Soil at Riau [82]
		2.76–4.49	2.61–3.40	9.38–10.15	11.73–15.30	54 months	Dry land, Bogor, West Java [86]
		1.62	2.03	3.24	4.06	2 years	Dry land, Cianjur West Java [85]
		4.21	5.25	16.84	21.0	4 years	Dry land, Cianjur West Java [85]
		4.25	5.97	17	23.9	4 years	Dry land, South Kalimantan [35]
		2.09	3.86	22	40.5	10.5	Dry land, West Java [78]
		1.70	1.72	2.59	3.74	2 years	Peat soil Pelalawan District, Riau [16]
		22.1	35.9	2.76	4.48	8 years	Dry land, Pakenjeng, Garut, West Java [29]
3	*F. moluccana*	1.7.	1.93	3.49.	3.87	2 years	Trial site (Gunungkidul)
		3.31	2.77	496.8	4.16	18 months	Dry land, Ciamis, West Java [14]
		182	1.85	364	3.69	2 years	Dry land, Panjalu West Java [91]
		2.34–3.9	3.74–3.76	11.7–20.5	11.3–18.7	3–5 years	Dry land, Kediri, East Java [92]
		3.64	4.74	7.28	9.48	2 years	Sandy Soil, Dry land, Tasikmalaya West Java [47]
		1.485	1.53	1.98	2.04	9 months	Dry Land Tasikmlaya West Java [47]
4	*A. mangium*	1.40.	1.26	2.81	2.52	2 years	Trial Site (Gunungkidul)
		2.67	2.23	401.3	3.35	18 months	Dry land Ciamis, West Java [14]
		2.23	2.17	134	13	6 years	Dry land, Guangdong China [88]
		1.8–5.8	1.4–7.3	10–15	15	2–3 years	Dry land at Some sites [30]
		3.71	4.50	5.57	6.76	18 months	Dry land, Malaysia [73].

4.4. Mixed Planting Designs

In selecting tree species for planting, reviewing the performance of the species under conditions similar to those of the intended planting area is paramount. This process can be used as the basis to determine tree species for specific locations and conditions, for example, in mixed-species community forestry plantations with teak in Gunungkidul. Based on the current study results, *G. arborea* and *N. cadamba* are more suitable among the four fast-growing tree species tested. *Gmelina arborea* demonstrates good survival, growth, and drought tolerance under prevailing Gunungkidul conditions (Figures 3 and 4). It also fits the socioeconomic production–harvesting scenarios for intercropping smallholder teak systems—compatibility with teak, short rotation, and available markets. Potential problems with *G. arborea* are reliable access to seeds of adequate quality and quantity [4]. Similar germplasm issues have been reported in Tamil Nadu, India [93]. Trials of *G. arborea* in Costa Rica, the Philippines, and Indonesia report poor stem forms [10]; however, extensive international trials determined that local *G. arborea* provenance is often the most suitable, including for Southeast Asia [94]. Breeding programs to produce *G. arborea* for dry sites have been conducted in Hojancha, Costa Rica [95]. In the dry land of Costa Rica, tree improvement programs for *G. arborea* achieved gains of around 20% [96].

Despite its low survival, *N. cadamba* demonstrated good growth (Figure 4). *Neolamarcka cadamba* has a great potential in reforestation and agroforestry programs, especially when provided with adequate nutrients [97]. In forest plantation establishment, optimum survival and growth of *N. cadamba* may be obtainable through amendment of soil and the supply of adequate water [97]. Treatment with four tons of biochar/ha and watering three times a week demonstrated increased survival and growth in the field [97]. Practical application of supplemental water may be a challenge in locations far from a teak's site. Low survival can be caused by genetic material that is not suitable for dry sites. A trial of seven *N. cadamba* seed populations in various parts of Indonesia documented seed resistance to drought variations. In drought-prone marginal sites, drought-resistant populations may provide the best option for the successful establishment of *N. cadamba* [75].

Based on the results of this study, although the growth rate of *A. mangium* was poor (Figure 4), the survival was good (Figure 3). Therefore, advanced evaluation of its growth rate is required in the years to come. *F. moluccana* is not recommended as a companion timber crops for teak. On dry land with rocky soil where the smallholder teak system has been established, *F. moluccana* did not perform well. Both the survival and growth of *F. moluccana* were poor. The site requirements of teak and *F. moluccana* are different; thus, this species is not compatible.

In India, recommended companion timber crops for teak include medium rotation timbers (*Dalbergia latifolia* and *Dalbergia sissoo*), short rotation timbers (*Schleichera oleosa* and *Acacia catechu*), and leguminous species as protective functions (*Acacia auriculiformis* and *Leucaena glauca*) [13]. In Burma, Nigeria, and India, *G. arborea* is commonly grown with teak [98]. Teak and *G. arborea* have the highest quantity of litter and a faster rate of decomposition, which is an index of high nutrient release to soil under this combination (compared mixed with *Khaya* sp and *Terminalia* sp) [99]. Smallholder teak systems in Gunungkidul contain other tree species, namely *Swietenia macrophylla* (11.3%), *A. auriculiformis* (5.8%), *Cocos nucifera* (5.8%), *Gnetum gnemon* (8.5%), *Leucaena leucochepala* (7.4%), and *Senna siamea* (1.1%) [22]. The leguminous tree *Sesbania grandiflora* is also commonly grown with teak in Gunungkidul.

In this study, the average crown area of the four species were *A. mangium*—8.0 cm^2. *G. arborea*—17.8 cm^2, *N. cadamba*—28.0 cm^2. and *F. moluccana*—18.8 m^2 (Figure 3). These crown areas will not disturb the slower growing teak plants. Adequate sunlight would remain for the neighboring teak, which is an intolerant species (light demander). Limited crown competition is an important factor to consider in designing a composition of mixed teak plantations [13]. Teak and *G. arborea* established in Nigeria showed that tree crown area correlated with stem form and tree size [59]. The development of mixed teak systems should consider various factors, including crown area, root characteristics, and growth pattern of the companion tree crops [13]. In the Solomon Islands, mixed teak and *F. flexuosa* systems cycle higher rates of C and N than teak monocultures [21]. This 50% teak and 50% *F. flexuosa* is thinned at five years by harvesting all of the *F. flexuosa*. In India, teak is intercropped with *Leucaena* as a nitrogen-fixing nursery crop, and there is one row of teak for every two rows of *Leucaena* [96].

Mixed plantations of teak should be carefully designed, emphasizing species with complementary growth characteristics [13]. Teak is recommended as the dominant species, with a short rotational crops (5–10 years) as the companion species to produce less valuable wood [13] but a short-term income. The cropping patterns can be alternating rows of teak and fast-growing timber species with 3 m × 3 m plant spacings [56,100]. The first thinning, the harvest of the short-rotation species, can be done between ages 5–8 years. By harvesting all short rotation species, the thinning intensity will be 50%, doubling the spacing post-harvest to 555 tress/ha. This fits the general guidelines for small teak in monoculture or mixed plantings [54,57,101]. The main advantages of a mixed planting design are (1) the management is much simplified; (2) the crop can be harvested economically and has an economic return; and (3) artificially restocking, if necessary, is simpler [102]. In addition to the canopy area, the basal area is a consideration in intercropping agricultural crops on timber plantations. The basal area and volume of *G. arborea* and *N. cadamba* were higher than *A. mangium* and *P. falcataria*. This effectively means that under a *G. arborea* stands, the planting area for agricultural crops is smaller. Many farmers reported intercropping their teak systems (mainly tegalan) with agricultural crops: cassava (26.6% of intercropped parcels), peanuts (23.8%), upland rice (18.0%), soybeans (8.1%), and long beans (*Vigna unguiculata* subsp. sesquipedalis, 2.9%) [22]. Farmers with more lands, higher incomes, and off-farm jobs prefer to invest in timber species or crops with a long rotation and a premium value. Meanwhile, farmers with limited incomes and lands decide to grow short-rotation timber species [103].

5. Conclusions

The selection of short-rotation timber species as companions to teak is very important for the successful development of mixed plantations that provide more benefits to farmers than monocultures. A mixed row system of teak and short-rotation timber species in community forestry and smallholder teak systems enables the first thinning at 5–8 years to be a commercial operation. Commercial thinning of short-rotation timber species will provide short-term income to farmers and enhance the productivity of the remaining teak stand. *Gmelina arborea* produces the highest viability (87.3%) and the best growth performance (17.64 m^3/ha) at the study site. *Neolamarckia cadamba* produces great growth (7.86 m^3/ha), although a low survival (40.6%) due to its drought vulnerability in the dry-rocky soil of the study site. A literature review indicates that survival of *N. cadamba* can be improved through fertilization and biochar treatment. *Acacia mangium* that successfully survives (78.2%) produces low growth (3.01 m^3/ha). Therefore, advanced evaluation of its growth rate in following years is required to ensure its feasibility as a teak companion in mixed planting. *Falcataria moluccana* produces the lowest survival (18%) and growth (1.38 m^3/ha) at the study site, so it is not recommended for mixed plantations with teak. Based on the growth performance of the study site and the characteristics of the growing site, which are similar to teak, *G. arborea* and *N. cadamba* are recommended as teak companions in mixed planting. These short-rotation timber species mixed with teak will be harvested at 5–8 years of age during the first commercial thinning. Intercropping short-rotation timber species and agriculture crops will encourage farmers to adopt silvicultural management and a more commercial orientation for their teak systems. Therefore, silvicultural treatment to allow fast-growing timber species to survive drought (5-month period without a day of rain) at the beginning of growth is very important. The dynamics of dry months and rainfall/months that may occur in the next periods need to be anticipated by selecting drought-resistant species (genetic material). Short-term and more diverse income will enable farmers to cultivate their land more intensively. Ecologically, trees also reduce erosion risks due to their extensive and strong root binds with rocks in the forest ground, especially in the Gunungkidul area. Teak and short-rotation timber species in the mixed pattern will provide farmers a real market advantage, provided that proper silvicultural management is applied. Intensive silviculture is needed to enhance the productivity of teak systems in drought-vulnerable dry-rocky soils in Gunungkidul.

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