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Tree diameter performance in relation to site quality in smallholder timber production systems in Gunungkidul, Indonesia

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Abstract Smallholder farmers' choices of tree species in the Gunungkidul region have been limited by lack of management information. This paper describes activities to help inform farmers' choices of three common timber species—*Tectona grandis*, *Swietenia macrophylla* and *Acacia auriculiformis*—in agroforestry systems in the region through (1) developing models predicting tree diameter growth based on reference growth function and the growth retardation performance and (2) estimating the contributions of site quality variables to the diameter growth retardation of ≤5 and >5-year-old stands. A total of 48 farms were selected, representing three slope ranges and two soil types, with a circular sample plot of 10 m radius established at each farm. A Quadratic model for each timber species indicated that the age of the tree explains a high percentage of the variance in diameter growth. Diameter growth varies with tree age and responds differently in each soil type and slope position. A set of site quality variables were able to predict retarded diameter performances of each tree species in two group ages and two soil types. These results suggest that the models can inform farmers' choices of tree species and management.

Keywords Smallholder farmers · Diameter growth retardation · Biophysical characteristics · Multiple regression

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Introduction

The forest transition model illustrates that as forest resources decline under various pressures, tree planting in various forms begins to restore tree cover (Snelder and Lasco 2008). The Gunungkidul region, Java, Indonesia, exemplifies this forest transition at a sub-national scale. In the region in the 1950s and 1960s, approximately 80 % (119,151 ha) of forest land was converted to agricultural production to meet the needs of the growing population, resulting in a reduction of tree cover on hillsides. This situation began to change when individual households established agroforestry systems (*kitren*/woodlots, *tegalan*/alley-cropping and mixed systems) on their own land by intercropping annual and timber trees, such as teak (*Tectona grandis*), mahogany (*Swietenia macrophylla*), and acacia (*Acacia auriculiformis*) with uneven-aged stands to suit households' objectives and to regenerate the productive capacity of soils in degraded landscapes (Filius 1997; Nibbering 1999). Rohadi et al. (2011) reported that farmers with small farms (<0.5 ha) in Gunungkidul allocated around 10 % of their land for growing timber trees.

The timber species planted differ in growth rate and yield across the sites. This indicates the unfavorable growing conditions of the sites and the failure in selection of appropriate species (Santos-Martin et al. 2010). Manson et al. (2013) added that a lack of knowledge for matching tree species to site is another impediment to successful agroforestry systems, since species performance can varies greatly between sites. Therefore, matching tree species to biophysical characteristics of a site should be aimed at maximizing yield by minimizing growth variability, ensuring the sustainability of site quality resources and improving silvicultural management practices of agroforestry systems (Nghia 1996; Roshetko and Evans 1999). Variation of individual tree growth in agroforestry systems is primarily affected by variations in the patterns of tree locations, variations in tree age, and site variability (SAFODS 2002).

Nowadays, tree site matching is approached from three different perspectives (Lusiana and van Noordwijk 2006). From the tree's perspective, the aim is to identify suitable sites based on reference growth function. From the sites' perspective, the aim is to identify the best tree species based on the contribution of site quality to tree growth. From the farmers' perspective, aim is to achieve the benefits of a given tree species and site combination. In this study, the analysis is focused on the combination of tree species and site approaches.

Despite the importance of tree species and site matching, farmers have their own perceptions regarding selection of tree species for their agroforestry systems. Tree use value, marketing opportunities and land tenure status are the main important factors affecting farmers in selection. The slope and soil quality, land elevation and annual rainfall were less important in species' selection for them (Manurung et al. 2008). This indicates that matching tree species to sites is of very little importance to the farmers. As a consequence, the achievement of high yields from tree species is hampered.

The aim of this study is to provide the necessary information for smallholder farmers to evaluate the diameter performance of selected timber species—teak (*Tectona grandis*); mahogany (*Swietenia macrophylla*) and acacia (*Acacia auriculiformis*)—and site matching to create better performing agroforestry systems. Specifically, this study has two objectives: (1) develop models predicting tree diameter performance based on reference growth function and the growth retardation factor and (2) estimate the contribution of site quality variables to the diameter growth retardation of ≤5 and >5-year-old stands.

Materials and methods

Site and soils description

The district of Gunungkidul is situated in the southeast of the Special Province of Yogyakarta, Java, Indonesia, between 7°46′–7°09′ south latitude and 110°21′–110°50′ east longitude. The district has hilly topography in its northern zone (Baturagung Mountain Range), the middle zone is relatively flat and called the Wonosari Plateau, and in the western, southern and eastern zones the Sewu Mountain Range (Gunung Sewu) is dominant. Slopes ranging from 2 to 40 % occupy about 71 % of the district and approximately 74 % of Gunungkidul is covered by the karst landscapes of Gunung Sewu and the Wonosari Plateau, dominated by Mediteran. The Baturagung Mountain Range features mostly Latosol and Renzina soil types, based on Indonesia soil classification (BAPPEDA Gunungkidul regency 2013). Mediteran and Renzina soils are equivalent to Alfisols and Mollisols, respectively, in the USDA soil classification (Subardja et al. 2014; Soil Survey Staff 2014). Elevation varies from 0 to 800 m above sea level (Statistics of Gunungkidul Regency 2014). The climate of Gunungkidul is strongly influenced by the wet northwest monsoon (November–April/May) and dry southeast monsoon (June–September/October). The range of annual rainfall is 1500 to 2000 mm and temperatures vary between 24 and 26 °C (Sudiharjo and Notohadiprawiro 2006).

Research design and sampling procedures

Farmer-collaborators and sites selected for the study were a subset of those described in Rohadi et al. (2011). A nested sampling technique was employed to select sites representing:

1. The three principle timber tree species: *Tectona grandis*, *Swietenia macrophylla* and *Acacia auriculiformis*;
2. The three slope classes represented in the district, namely, (a) 0–15 %; (b) 16–30 %; and (c) >30 %; and
3. The two different soil types (Alfisols and Mollisols) in the district.

The farmer-collaborators were selected from five villages with the two soil types, of which, four villages (Giripurwo, Giripanggung, Dadapayu and Bejiharjo) featured the more common Alfisols and one village (Candirejo) the less common Mollisols.

The total number of sampled farms was 48, with a 10 m radius circular plot (314 m^2) established at each farm. The 48 circular plots were located in 24 woodlots, 10 alley-cropping and 14 farms where the agroforestry systems were mingled. The number of farms was determined by the sample necessary to represent three slope classes and two soil types. Since Alfisols were distributed over a larger area, covering four of the sampled villages, the number of farms for each slope range in this soil type was replicated nine to 11 times. In the less common Mollisols soil type, six replications were used for each slope class. Each of the sites belonged to a different farmer, who determined, and implemented, all on-farm activities; consequently, management of the farms varied from site to site.

Tree biometric information [diameter at breast height (dbh) and age] and Site Indicators consisting of Landscape Condition (slope, elevation and annual rainfall), Soil Texture (sand, silt and clay) and Soil Chemical Property (pH H_2O, C-organic, N, P, K and cation exchange capacity (CEC) were gathered from the circular plots during a series of field surveys. The tree dbh was measured at 1.3 m height from the soil surface, while the age of the tree was provided by the farmer. A Suunto clinometer was used to measure the percent scale of the slope and the elevation of the farm was measured using a Garmin GPS. The soil samples were taken from the top layer of soil (25 cm depth without litter) in each circular plot; five-to-six holes were sampled with a total of about one kilogram collected. The raw soil samples were processed and analysed by the Indonesian Soil Research Institute in Bogor, for nine variables, namely, (1) clay (%); (2) sand (%); (3) silt (%); (4) pH H_2O; (5) C-organic (%); (6) N (%); (7) P-available (ppm); (8) K (ppm); and (9) CEC (cmol/kg). Individual soil textures and nutrient status of soil samples were assessed using the criteria of the Indonesian Soil Research Institute (ISRI 2009). A time series of 27 years of annual rainfall data for the area was obtained from the Agricultural Agency of the Gunungkidul district government.

Data analysis and model building

Data analysis and model building was a three-step process. The first step identified the individual and combined effects of slope range and soil type on dbh growth of each tree species using the Two-way ANCOVA analysis. In this analysis, tree age was employed as covariate to other independent variables. The second step tested different models to relate the observed diameter (dbh) with the observed age (t) of each tree species (teak, mahogany and acacia). Using dbh as dependent variable and t as independent variable, the Quadratic model ($dbh = at2 + bt + c$) was employed as it turned out to be the best fit with the highest R^2 value. In the Quadratic model, trees which are below the reference growth curves grow slower than the average. The retardation in diameter growth may be due to site conditions, management, germplasm or errors of measurements. Furthermore, Lusiana and van Noordwijk (2006) argued that the relation between the observed and expected age of an individual tree given its growth performance can be defined as the growth retardation factor (GRF). Mathematically, the GRF is defined as following:

$$GRF = \ln\left(\frac{t_{observed}}{t_{expected}}\right) \quad (1)$$

where the $t_{expected}$ was calculated as:

$$t_{expected} = \frac{-b \pm \sqrt{b^2 + 4a\left(dbh_{observed} - c\right)}}{2a} \quad (2)$$

with a, b and c the quadratic, linear, and constant coefficients of the quadratic equation for each tree species, respectively.

The third step used multiple regression analysis to build a model for each tree species to estimate the contribution of site variables (elevation, slope, sand, silt, clay, pH H_2O, C-organic, N, P, K, CEC and annual rainfall) on diameter growth retardation for ≤ 5 and >5-year-old stands. Standardized coefficients (β-values) for each variable were used to compare the contribution of each variable to retarded diameter performance. The resulting tabular data containing site quality variables of trees were exported to the SPSS (Statistical Package for the Social Sciences) version 19 statistical program (Pallant 2007).

Results

Tree density and species identified

The total number of trees assessed in the 48 circular plots was 2606, where 48 % had dbh $\leq$ 5 cm. Mean tree density per hectare for the two different soil types (Alfisols and Mollisols) was 1764 and 1670 trees, respectively; while tree density per hectare in Alfisols and Mollisols for slope ranges 0–15, 16–30 % and >30 % was 2073, 1694 and 1507 trees and 1991, 1354 and 1667 trees, respectively. Tree density per hectare for woodlots, alley-cropping and combined agroforestry systems was 2154, 742 and 1706 trees, respectively. On average, six tree species were present in each plot; the composition of the tree species for each production system is illustrated in Fig. 1. Teak was the dominant species (around 45 % of all trees); mahogany was the next most frequent (around 25 %); the combined frequency of other species was slightly greater than that of acacia (around 15 and 13 %, respectively). The species' composition in woodlots and alley-cropping settings was very similar for most species.

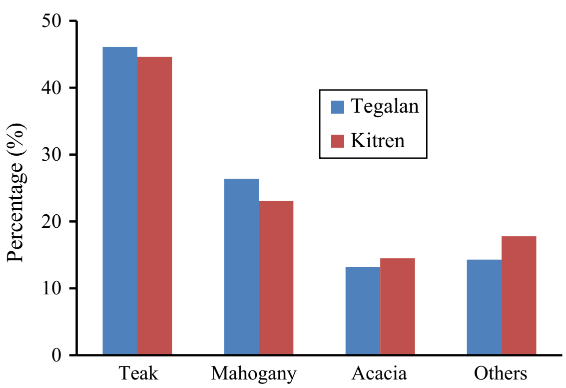

Fig. 1 Tree species' composition (%) in Tegalan (Alley-cropping) and Kitren (Woodlots)

Site characteristics

The averages of soil texture and fertility ratings for farm sites in similar slope ranges are shown in Table 1. In general, soil texture varied from clay to sandy clay loam across sites in Gunung Sewu, Wonosari Plateau and Baturagung Mountain Range. Clay dominated the soil texture of the Alfisols of Gunung Sewu and Wonosari Plateau, with the clay content in most horizons being more than 42 %. In the Alfisols, sand content was in the range of 3–40 %. However, in the Baturagung Mountain Range where the Mollisols dominated, the predominant soil texture was sandy clay loam with a minimum sand content of 51 %.

The soil fertility rating of the sites was diverse. According to the criteria of the Indonesian Soil Research Institute (ISRI 2009), concentrations of organic C and N in the Alfisols and Mollisols soil types were low, less than 1 % for C-organic and 0.1 % of nitrogen, respectively. In contrast, average P and K concentrations were at medium to very high levels: more than 10.6 and 58 ppm, respectively. Mollisols and Alfisols were slightly acid; the CEC of both soil types was high, within the range 25–40 cmol/kg.

Tree growth performance

Tree growth performance of timber species was evaluated using Two-way ANCOVA, Quadratic equation, and growth retardation factor (GRF). The effects of slope range and soil type on the diameter of trees were analysed using the Two-way ANCOVA method. The individual and combined effects of slope range and soil type did not affect tree growth significantly, reaching just 5 %. In Mollisols, the highest growth performance of teak, mahogany and acacia trees was on slopes of more than 30 %. However, the growth performance of tree species varied in Alfisols, where teak, mahogany and acacia grew best in slope ranges of >30, 0–15, and 16–30 %, respectively (Fig. 2).

As the timber trees are uneven-aged stands grown on the farms, the owners of the farm assisted to observe and determine the age of each individual timber tree during dbh measurement. Diameter (dbh) performance in relation to the age of the tree for each of the selected species as influenced by the site qualities in both Alfisols and Mollisols was modelled using the Quadratic equations as shown in Figs. 3 and 4.

Table 1 Site quality for sampled farms

Farm sites	Slope range (%)	Soil type (USDA)	Elevation (m asl)	Sand (%)	Silt (%)	Clay (%)	pH H_2O	C-organic (%)	N (%)	P (ppm)	K (ppm)	CEC (cmol/kg)	Annual rainfall (mm/year)
1–10	0–15	Alfisols	231	11	23	67	6.6	1.2	0.1	5.2	66.2	26.9	1748
11–21	16–30	Alfisols	257	8	41	51	7.2	0.7	0.1	8.2	82.9	29.6	1834
22–30	30+	Alfisols	282	14	44	42	6.9	0.6	0.1	12.9	83.2	29.6	2017
31–36	0–15	Mollisols	160	58	19	24	5.6	0.5	0.0	15.7	202.4	41.0	850
37–42	16–30	Mollisols	252	56	22	23	5.2	0.8	0.1	7.6	106.7	32.0	850
43–48	30+	Mollisols	221	51	22	27	6.0	0.8	0.1	14.2	119.7	35.9	850
Fertlity rating[a]							Slightly acid	Low	Low	Medium	Very high	High	

[a] Source: Indonesian Soil Research Institute (2009)

For Alfisols, the fitted model for each timber species indicates that 73–85 % of the variance in dbh can be explained by the age of the tree, suggesting that the general pattern of growth is similar for each species. As the coefficient values of the Quadratic growth model show (Fig. 3), teak was the slowest-growing species and acacia was the fastest, on all farms. In Mollisols (Fig. 4), the variances in the fitted models for all species show 79–89 %. However, mahogany was the slowest-growing species compared to other timber species.

Based on the above-reference growth functions, the growth retardation factor (GRF) was calculated for every observed tree in Alfisols and Mollisols (Figs. 5, 6). In general, the distribution of GRF values for older trees (>5-year-old) in Alfisols was only within the range of ±0.7, while for younger trees (≤5-year-old) the range was expanded to ±1.0. The distribution range of GRF for older and younger trees in Mollisols was ±0.4 and ±0.7, respectively. This indicates that the dbh variation among young trees is higher than for older ones. However, about 50 % of young trees experienced below-average tree growth, indicated by the negative values of the GRF.

Contribution of site quality to the growth retardation factor (GRF)

The results of a multiple regression analysis describes the effects of a set of site quality variables on the GRF value of younger and older trees in both soil types (Tables 2, 3). The annual rainfall variable for sites 31–48 was deleted from the analysis since the annual rainfall values are constants (Table 1).

For teak grown in Alfisols and Mollisols, the regression models of GRF of ≤5-year-old trees indicate that 50–56 % of the variation of GRF can be explained by site quality variables (Tables 4, 5). Increasing phosphorus in Alfisols and decreasing land slopes decreased dbh performance of younger trees, while no variables affected the delaying of diameter growth of the trees in Mollisols. For older trees, the models show that 67–69 % of the variation of GRF can be explained by the variables. The models indicate that decreasing soil CEC and increasing phosphorus in Alfisols, and decreasing the silt content of Mollisols retarded diameter growth of older trees.

The regression models for younger and older mahogany trees on Alfisols show that only 29 % of the variation of GRF can be explained by site quality variables; however, no variables have significant effects on GRF values (Tables 2, 3). In Mollisols, there were 83 and 73 % of the variations of GRF can be explained by the variables in the models for younger and older trees, respectively (Tables 4, 5). Decreasing soil silt and phosphorus content, increased farm elevation slowed the diameter growth of younger trees, while diameter growth in older trees was slowed by due to increased soil acidity, farm elevation and decreases in land slopes, and soil clay and phosphorus content.

The retardation of diameter growth in younger acacia trees was significantly affected by the

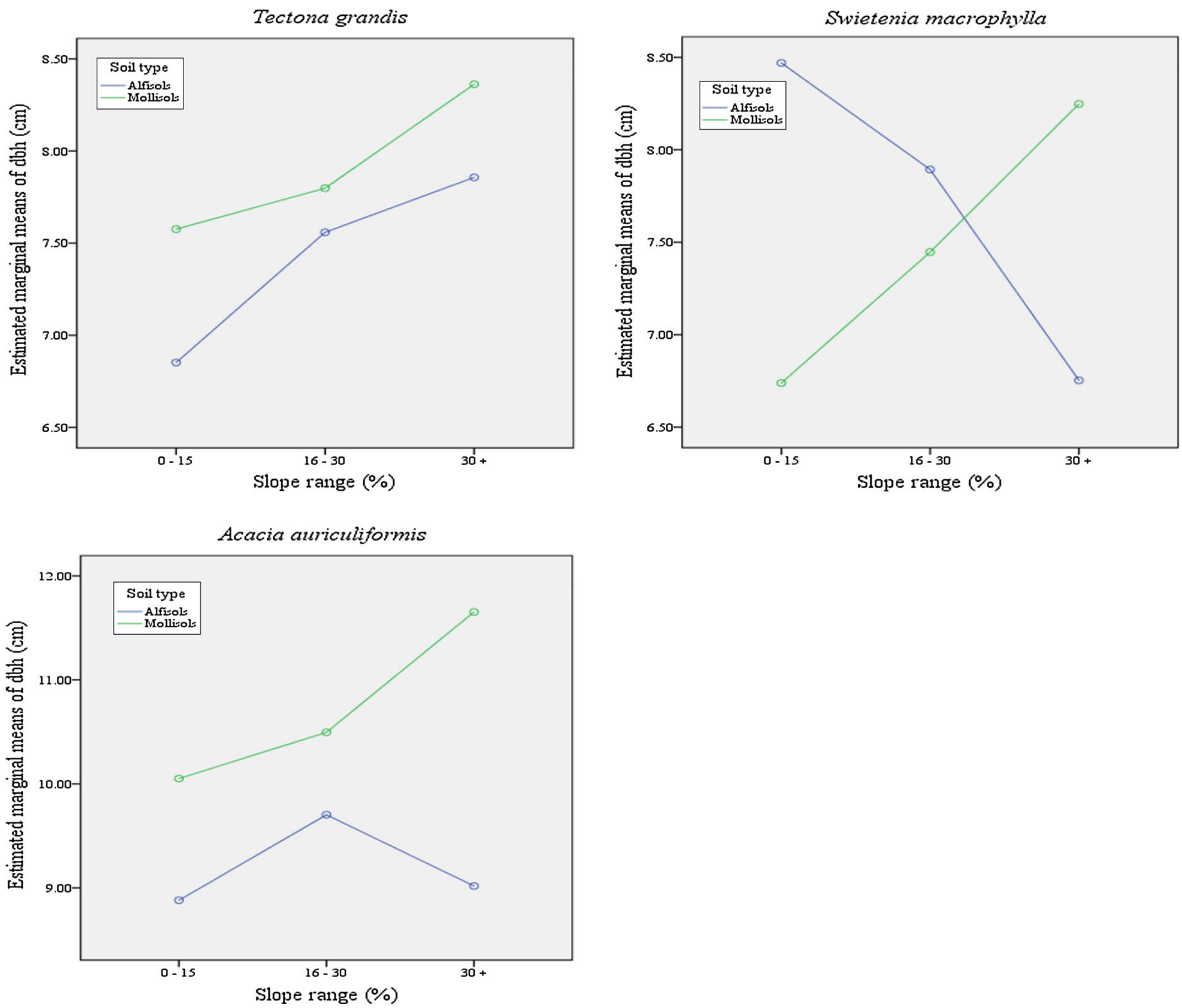

Fig. 2 Diameter (dbh) growth in relation to slope ranges and soil types

decreasing of land slopes and increasing of soil CECin Alfisols and the decreasing of soil acidity in Mollisols, respectively (Tables 2, 3). This retarded diameter performance resulted in the regression models with GRF variation spanning 54–59 % (Tables 4, 5). For older trees, there were no significant variables causing retarded diameter growth and the variation of GRF that can be explained by the variables was quite low (34 and 43 %) in the regression models of both soil types.

The variation (R^2) of GRF for younger and older trees of timber species increased when site indicators were individually added into the regression models of both soil types (Tables 4, 5). In general, the addition of site indicators (landscape condition, soil texture and soil chemical properties) into the models increased the R^2 values significantly.

Discussion

Study results show that farmers grown their timber trees with high tree density in Alfisols and Mollisols. There is indication that tree density per hectare higher on the woodlots and lower slopes. The preference of farmers in planting trees is to have more trees rather than to improve the quality of trees for producing logs. Also, this overstocked tree stands led to high competition on soil nutrients between the trees; therefore, it implicated to declining the content of nutrients in the

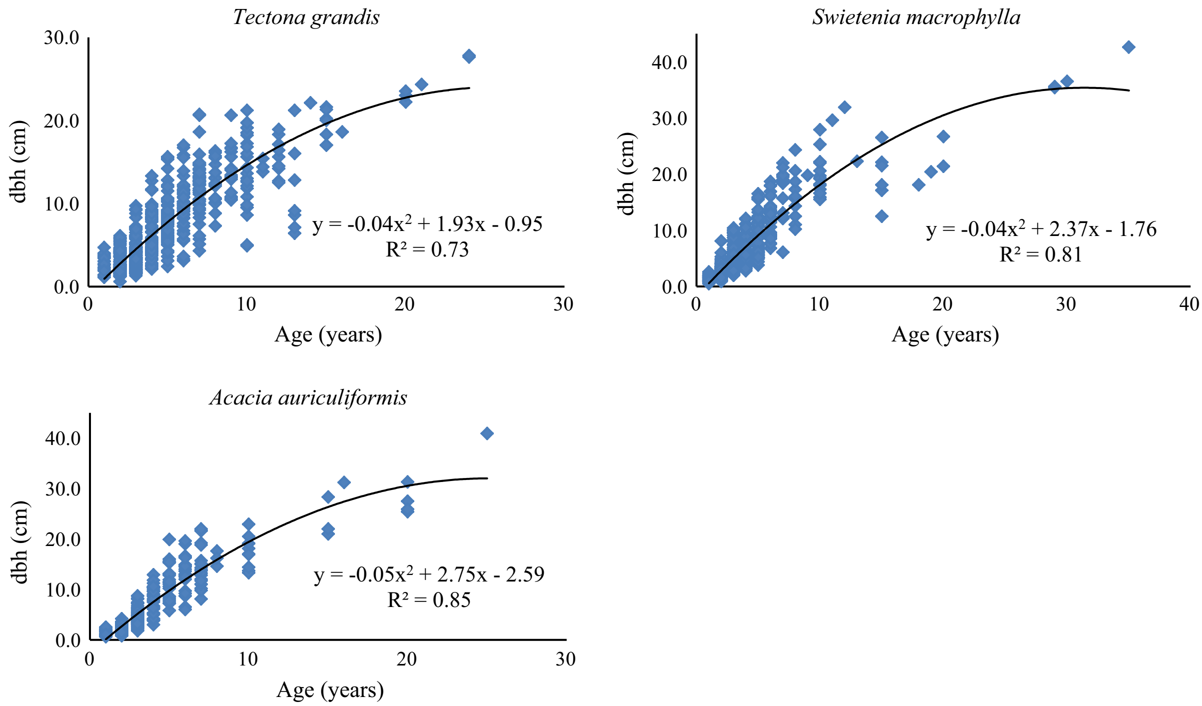

Fig. 3 Reference growth functions for each timber species in Alfisols

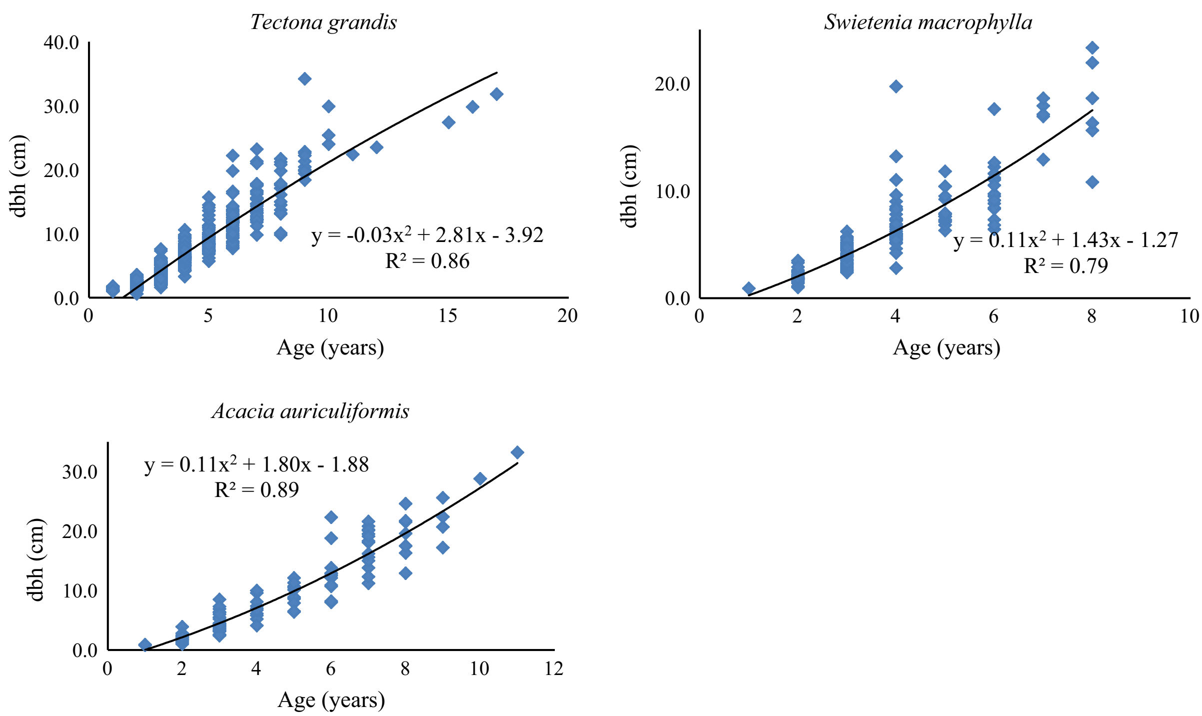

Fig. 4 Reference growth functions for each timber species in Mollisols

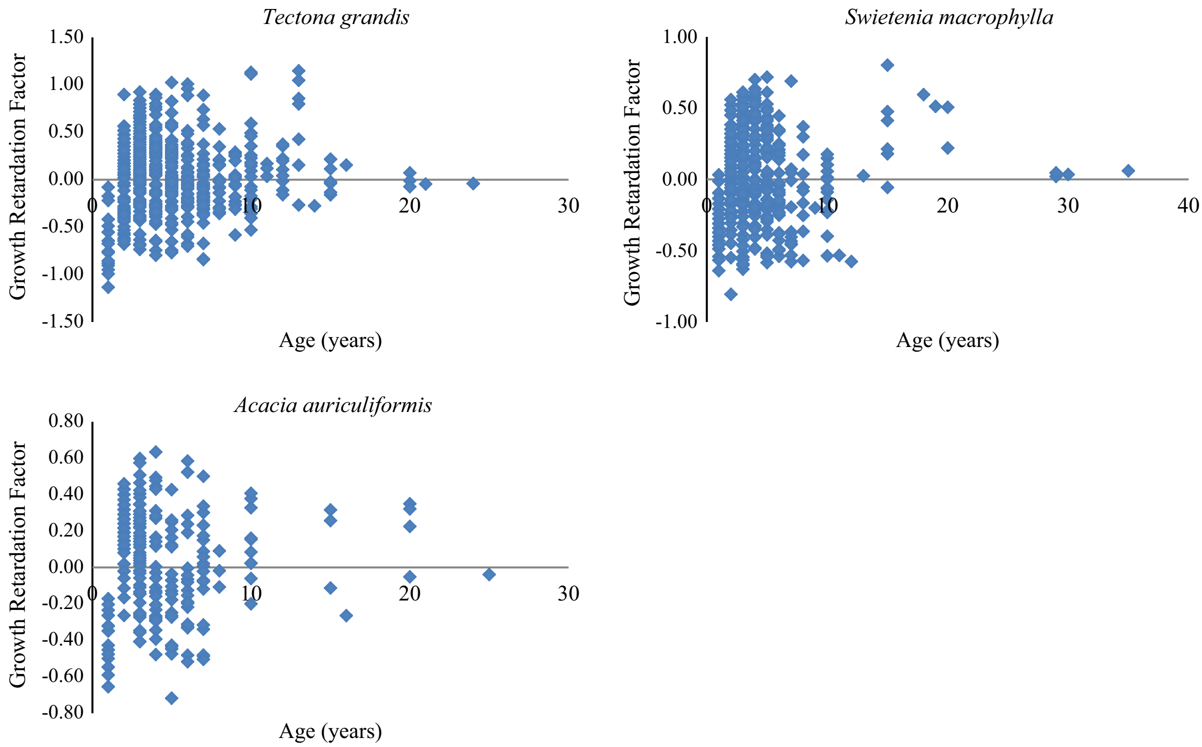

Fig. 5 Growth retardation factor (GRF) for each timber species in Alfisols

soils. Roshetko et al. (2013) summarized that the management practices of smallholder timber production systems were indicated as overstocked, slow growing and of suboptimal quality and production.

Site quality at the research farms varied. Table 1 show that the low content of C-organic and N in the soils was caused by the slow decomposition processes of organic matter. Degraded sites with dominant limestone landscapes and low levels of soil organic matter and nitrogen, such as the Gunungkidul region, were characterized by lower growth rates, especially in young stands, as confirmed by the negative values of GRF. Siradz (2004) found that Alfisols of Gunung Sewu and Wonosari Plateau limestone landscapes have an imbalance of nutrients, with slow decomposition rates of organic matter owing to low soil moisture. Soil nitrogen contents are also very low due to low organic matter. The landscapes contain high concentrated calcium (Ca), while the availability of soil phosphorus limited since the phosphorus was adsorbed strongly by calcium and becoming unavailable to plants. Lack of soil organic matter and slow rates of soil permeability, in turn, have a negative impact on tree and crop growth. Furthermore, Brown and Lemon (2014) argued that soils with a high CEC are more likely to develop abundances in potassium (K^{+}), magnesium (Mg^{2+}) and other cations; and provide a buffer against soil acidification. Therefore, high levels of potassium and CEC in the soils of Gunungkidul were implicated in the low acidity of soils.

There is often a strong statistical relationship between tree age and diameter (Rohner et al. 2013). In this study, tree diameter and age of teak, mahogany and acacia were correlated up to 89 % when using the quadratic model instead of other models. Therefore, under the varying conditions of farm sites in Alfisols, Mollisols and agroforestry systems, the diameter growth of teak and acacia trees was better in Mollisols than in Alfisols. Mahogany growth performed well in Alfisols when the trees were planted in the slope ranges 0–30 %. Differences in tree density per hectare and in soil phosphorus, potassium and CEC concentrations between the various soil types led to differences in diameter growth of timber species.

For teak, it is not advised to grow younger trees with high tree density on lower slopes as increases in tree stands results in delayed diameter performance. In

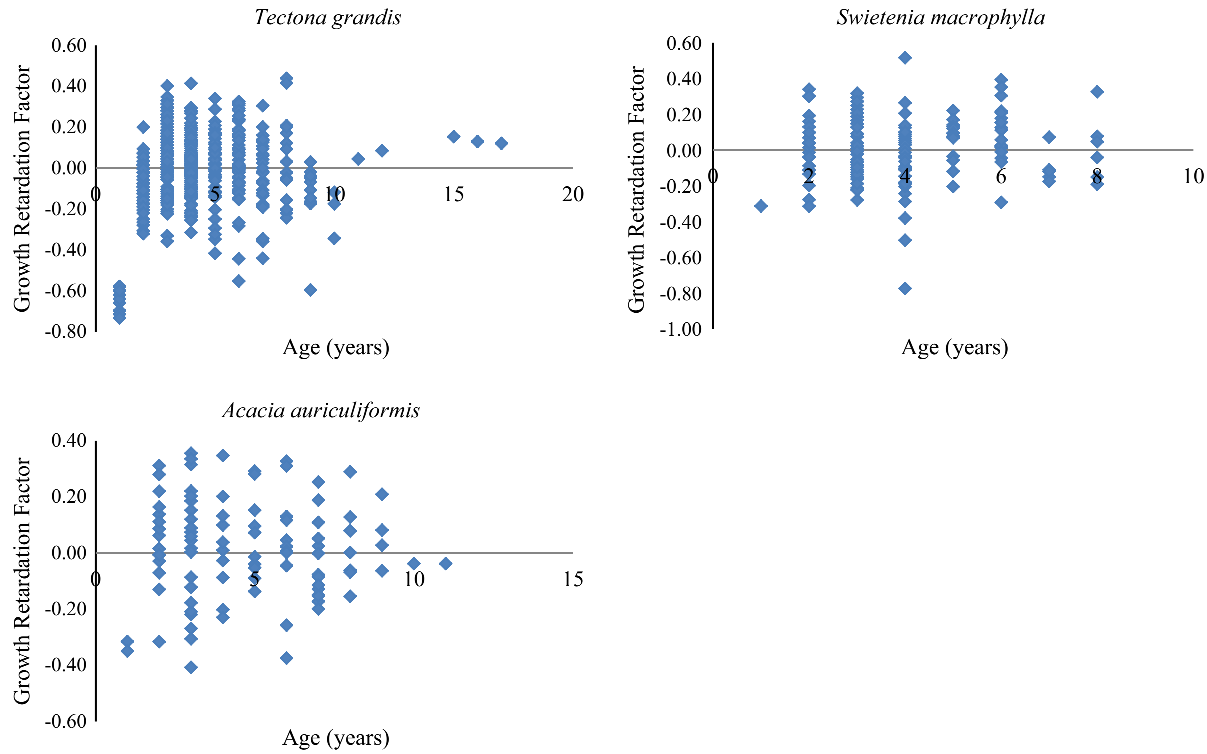

Fig. 6 Growth retardation factor (GRF) for each timber species in Mollisols

Table 2 Significance of site quality variables on growth retardation factor (GRF) in Alfisols

Model	*Tectona grandis*		*Swietenia macrophylla*		*Acacia auriculiformis*	
	GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)
Elevation	0.005	−0.178	0.618	−0.145	0.423	0.364
Slope	−0.542*	−0.112	−0.310	0.164	−0.552**	0.000
Sand	−0.001	−0.295	0.373	0.093	0.020	−0.146
Silt	−0.228	0.074	−0.075	−0.108	0.246	0.382
pH H_2O	−0.148	0.246	−0.409	0.086	−0.192	−0.127
C-organic	0.484	0.227	0.701	−1.771	−1.806	−1.973
N	−0.286	−0.027	−0.537	1.866	1.784	2.127
P	0.601*	0.538*	−0.187	0.086	−0.217	0.076
K	−0.333	−0.042	−0.191	−0.200	−0.223	−0.154
CEC	0.014	−0.808**	0.410	0.016	0.584*	0.021
Annual rainfall	−0.019	−0.221	0.101	0.411	0.369	−0.130

** Significance at 5 % level and * at 10 % level

the limestone landscapes of Gunungkidul, teak can grow well on slopes greater than 30 % with lower density of trees. Camino et al. (2002) and Kolmert (2001) reported that the best sites for teak in Costa Rica and Lao PDR were located in areas with medium-to-flat slopes. Kaosa-ard (1998) and Fernandez-Moya et al. (2015) reported that teak has been planted in a wide variety of soils, but the species requires relatively

Table 3 Significance of site quality variables on growth retardation factor (GRF) in Mollisols

Model	*Tectona grandis*		*Swietenia macrophylla*		*Acacia auriculiformis*	
	GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)
Elevation	0.240	0.113	0.621*	0.802*	−0.181	−0.053
Slope	−0.303	0.207	0.259	−1.295**	1.122	0.242
Silt	−0.374	−0.628*	−0.869**	−0.261	−0.397	−0.297
Clay	−0.627	0.386	−0.229	−0.737*	0.283	0.534
pH H_2O	0.456	−1.151	0.326	1.565**	−1.665*	−0.943
C-organic	1.642	−2.490	−1.628	2.569	−2.551	−0.968
N	−1.198	2.709	1.502	−2.138	2.195	0.649
P	−0.365	−0.412	−0.950**	−0.811*	−0.347	0.043
K	0.103	−1.030	0.418	1.018	−0.662	−0.572
CEC	0.418	1.172	−0.161	−0.423	1.342	0.579

** Significance at 5 % level and * at 10 % level

Table 4 Relationships between growth retardation factor (GRF) and site indicators in Alfisols

Site indicator			R^2					
Landscape condition	Soil texture	Soil chemical property	*Tectona grandis*		*Swietenia macrophylla*		*Acacia auriculiformis*	
			GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)
X			0.31	0.41	0.06	0.13	0.12	0.07
	X		0.10	0.08	0.01	0.05	0.04	0.15
		X	0.28	0.57	0.21	0.13	0.34	0.15
X	X		0.32	0.42	0.09	0.21	0.28	0.20
X		X	0.47	0.64	0.25	0.28	0.56	0.26
	X	X	0.33	0.60	0.21	0.16	0.45	0.32
X	X	X	0.50	0.67	0.29	0.29	0.59	0.34

large amounts of calcium, phosphorus, potassium, nitrogen and organic matter in the soils for its growth and development. Regardless of the low levels of organic carbon and nitrogen, Soerianegara and Lemmens (1994) added that a soil pH of 6.5–8.0 with relatively high calcium (Ca) in conjunction with high levels of soil CEC and phosphorus (P) content is required for teak to grow well in Java, Indonesia. Therefore, Alfisols (decreasing CEC and increasing phosphorus concentrations) and Mollisols (decreasing soil silt) should be avoided to prevent retarded growth of younger and older trees in the research sites.

Growth performance of mahogany varied in both soil types. There were no site quality indicators devoted to delaying diameter performance of mahogany in Alfisols, but six indicators were correlated with the delayed growth of mahogany in Mollisols. Mahogany trees are not recommended for planting at higher elevations and in Mollisols with low phosphorus content. Gentler farm slopes and higher soil acidity were correlated with slower growth in older trees which grown on higher tree density. As for soil textures, young trees cannot grow well in soils with low silt content, while older trees grow more slowly when there are low levels of soil clay. According to Soerianegara and Lemmens (1994), soil requirements for mahogany are largely unspecific. Therefore, the tree can still grow in soils derived from limestone in the Gunungkidul region (Tables 2, 3). Krisnawati et al. (2011) affirmed Soerianegara and

Table 5 Relationships between growth retardation factor (GRF) and site indicators in Mollisols

Site indicator			R^2					
			Tectona grandis		*Swietenia macrophylla*		*Acacia auriculiformis*	
Landscape condition	Soil texture	Soil chemical property	GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)	GRF (≤5-years)	GRF (>5-years)
X			0.02	0.05	0.08	0.16	0.01	0.08
	X		0.13	0.10	0.11	0.01	0.10	0.14
		X	0.39	0.40	0.45	0.40	0.25	0.26
X	X		0.15	0.20	0.29	0.18	0.13	0.26
X		X	0.40	0.43	0.50	0.55	0.42	0.27
	X	X	0.55	0.67	0.61	0.47	0.32	0.42
X	X	X	0.56	0.69	0.83	0.74	0.54	0.43

Lemmens' (1994) findings and added that the best performance of mahogany was on deep, fertile, well-drained soils with a pH of 6.5–7.5 with optimum annual rainfall between 1000 and 2500 mm.

Young acacia trees should not be grown with high tree density on the gentlest slopes, or on Alfisols with high CEC, or in Mollisols with low acidity, since these indicators contribute to delayed diameter performance of the trees. According to Pinyopusarerk (2001) and Orwa et al. (2009), *Acacia auriculiformis* tolerates a wide range of soil types from sandy loam to heavy clay textures with soil pH H_2O of 3.0–9.5. Kushalapa (1991) found that this species enriched the soil through litter and decreased soil acidity over a period of 8 years. Peng et al. (2005) and Combalicer et al. (2012) reported the ability of this species to improve soil fertility through nitrogen fixation at the tree roots. The existing acacia trees in Gunungkidul region have been appropriately used for rehabilitating the region's degraded land in the last few decades.

Regression models indicate that the diameter growth performance of tree species differs significantly depending on quality variables of the sites where they were grown in both soil types. These variations can be minimized by farmers through intercropping and silvicultural management practices, including quality germplasm, initial spacing, pruning and thinning in their timber production systems. Kumar et al. (1998) found that intercropping teak with *Leucaena* improved the diameter growth of teak and modified soil characteristics; while Roshetko et al. (2013) reported the combined 'thinning and 60 % pruning' treatment increased teak diameter by 60 % compared with the 'no thinning and no pruning' control. Bertomeu et al. (2006) and Sabastian et al. (2014) found that the management intensity of timber production systems, including widely spaced tree hedgerows was positively associated with higher on-farm income.

The models clearly show that the combination of landscape conditions, soil texture properties and soil chemical properties contributed to the highest R^2 values (Tables 4, 5). This means that the combination of site indicators is suitable to explain tree diameter performance for those species. Despite the relatively low variation of diameter performance that can be explained by the combination of site indicators, the farming techniques varied from site to site due to management preferences of the individual farmers, rather than being experimental plots for the study of predicting tree growth from soil and climatic factors. However, the methodology and scientific information in this study can be considered by researchers and decision makers to bridge farmers' limitations by providing 'tree species-site matching' maps for them.

Conclusions

Tree growth prediction using quadratic models demonstrated that more than 73 % of the variance in the diameter growth of the three selected tree species can be explained by the age of tree. The models show that teak and mahogany growth is slowest in Alfisols and Mollisols, respectively. Diameter growth varies with tree age for all species and responds differently in each soil type and slope position, with slower diameter growth at higher tree density on the gentlest slopes of Alfisols and Mollisols for teak and acacia, and on Mollisols and on medium to flat slopes for mahogany grown at higher tree density. Retarded diameter growth performance of timber species depended on the quality of the site where they were grown. The ability to model diameter growth retardation under a range of site quality indicators would be extremely useful when selecting tree species for smallholder timber production in Gunungkidul and, consequently, the development of a plantation strategy for sustainable agroforestry systems in this and other regions.

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