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Assessment of enrichment planting of teak (*Tectona grandis* L.f.) in degraded dry deciduous dipterocarp forest in the Central Highlands, Viet Nam

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Abstract

After years of unsustainable logging, dry deciduous dipterocarp forest (DDDF) has become poor in timber stocks and has been converted to industrial crops such as rubber. The objectives of this study were to assess teak (*Tectona grandis* L.f.) tree establishment under degraded DDDF conditions and to determine factors that influence the suitability of teak as a forest enrichment tree species. A set of 64 experimental plots of 4900 m^2 each was set up and observed for 4–5 years for testing enrichment planting with teak under various combinations of two groups of factors: ecological conditions and forest status. Weighted, non-linear, multivariate regression models were used to detect key factors that influenced the suitability of teak. The results showed that at the age of 4 years the average dominant tree height (defined as 20% of the tallest trees in the experimental plot) reached 11.2, 7.8, 5.3 and 3.8 m for very good, good, average, and poor suitability levels, respectively. Survival rates of planted teak from average to very good suitability levels were over 90%. Six key factors that affected the suitability of teak were waterlogging during the rainy season, altitude, stand volume of the degraded DDDF, soil type, percentage of sand and concentration of P_2O_5 in the soil. Under the extreme ecological and environmental conditions of the DDDF, enrichment planting with teak gave promising results.

Keywords: degraded dipterocarp status, dipterocarp enrichment, teak suitability assessment.

Introduction, scope and main objectives

Dry deciduous dipterocarp forest (DDDF) is a dominant forest type throughout South-east Asia (Maury-Lechon and Curtet 1998). In Viet Nam, this forest type covers approximately 650 000 ha that are mostly degraded and that are distributed in two main ecological regions: The Central Highlands and the South East (Huy et al. 2015). After years of exploitation, the DDDF timber quality has become impoverished. As a result, many forest areas have been converted to crops such as cashew (*Anacardium occidentale* L.), rubber (*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.) and acacia (*Acacia* spp.) (Huy et al. 2015). Clearing DDDF for cultivation brings the risk of long-term environmental degradation. There is a need to find economically valuable and environmentally suitable timber species to enrich the degraded DDDF (Wyatt-Smith 1963; Erskine and Huy 2003). Given the extreme ecological conditions of sites in the DDDF (e.g. forest fires and drought in the dry season, and waterlogging in the rainy season), it has been difficult to find a tree species with high economic value that can be used for enrichment planting in the degraded DDDF. Enrichment planting is a silvicultural technique that is often used to increase the economic values of degraded forests and therefore helps prevent the conversion of these forests to other land uses, thus reducing deforestation (Paquette et al. 2009). Enrichment planting was applied in dipterocarp forest management throughout the Asian tropics (Appanah 1998).

Teak (*Tectona grandis* L.f.) is a deciduous tree species that attains a height of 30–40 m under favorable conditions. Growth rates of teak, which depend on the site, vary from 2 to 30 m^3 ha^{-1} y^{-1}. The commercial harvesting cycle is from 4 to 80 years (Kollert and Cherubini 2012). ICRAF (2010) showed that teak could be 13 m in height and 10 cm in diameter under suitable conditions at the age of 5 years. In addition, teak is famous worldwide because of its attractiveness and durability, enjoying high demand in the global market.

White (1991) and Ladrach (2009) showed that the natural distribution of teak is in India, Myanmar, Thailand and Laos. There are approximately 23 million ha of natural teak forest, with almost half occurring in Myanmar (Roshetko et al. 2013). In addition, teak grows naturally in deciduous forests at a rate of 4–35% of density, growing together with some species present in DDDF (Kollert and Cheubini 2012). Teak is tolerant of a wide range of climates, from dry areas with rainfall of 500 mm y^{-1} to humid areas with rainfall of up to 5 000 mm y^{-1}, but the species grows best in warm, moderately moist, tropical conditions (Weaver 1993). The optimal growth of teak is in the range of 1 200–2 500 mm annual rainfall with a 3–5 month dry season, and temperatures of 27–36 °C (Kaosa-ard 1998).

Teak trees need direct sunlight and regenerated shoots grow well under canopy openings (Chowdhury et al. 2008). Teak can grow on a variety of soils that are developed from different bedrocks such as sandstone and shale. However, it requires well-drained deep soil with pH of 6.5–7.5. Dry sandy soils, shallow topsoil or waterlogged conditions result in reduced growth (Kaosa-ard 1998). Soils suitable for teak are relatively fertile, but the most important limiting factors are shallowness, hardpans, waterlogged conditions, compaction or heavy clays with a low content of calcium or magnesium (Weaver 1993).

Teak plantations have been established within and beyond the native distribution range of the species (Kanninen et al. 2004). Myanmar began planting teak using the Taunya system in 1856; teak was first planted in Nigeria in 1902 (Ladrach 2009). The global area of teak plantations is a minimum of 4.3 million ha, of which 83% is in Asia, with India, Indonesia and Myanmar having the largest areas (Newby et al. 2011; Roshetko et al. 2013; Sabastian et al. 2014). Teak was introduced to Viet Nam in the 1950s to establish plantations (Huy et al. 1998, 2015).

Despite past experience with establishment of teak plantations, there are differences between establishing a homogeneous plantation of teak or an agroforestry system with teak trees compared with enrichment planting of teak under the canopy of a degraded DDDF. The objectives of this study were (1) to assess the adaptability of teak trees to degraded DDDF conditions and (2) to monitor the growth rate of teak trees during the early stage of growth in degraded DDDF in the Central Highlands of Viet Nam.

Methodology

1. Study area and materials

We surveyed 91 088 ha of degraded DDDF in the Central Highlands of Vietnam (Figure 1). Forest density was 48–558 trees ha^{-1} and stand volume was 4–198 m^3 ha^{-1}. Most of the dominant tree species were members of the family Dipterocarpaceae, including *Shorea siamensis* Miq., *Shorea obtusa* Wall. ex Blume, *Xylia xylocarpa* (Roxb.) Taub., *Terminalia alata* Wall., *Terminalia chebula* Retz., *Dipterocarpus tuberculatus* Roxb. and *Dipterocarpus obtusifolius* Teijsm. ex Miq.

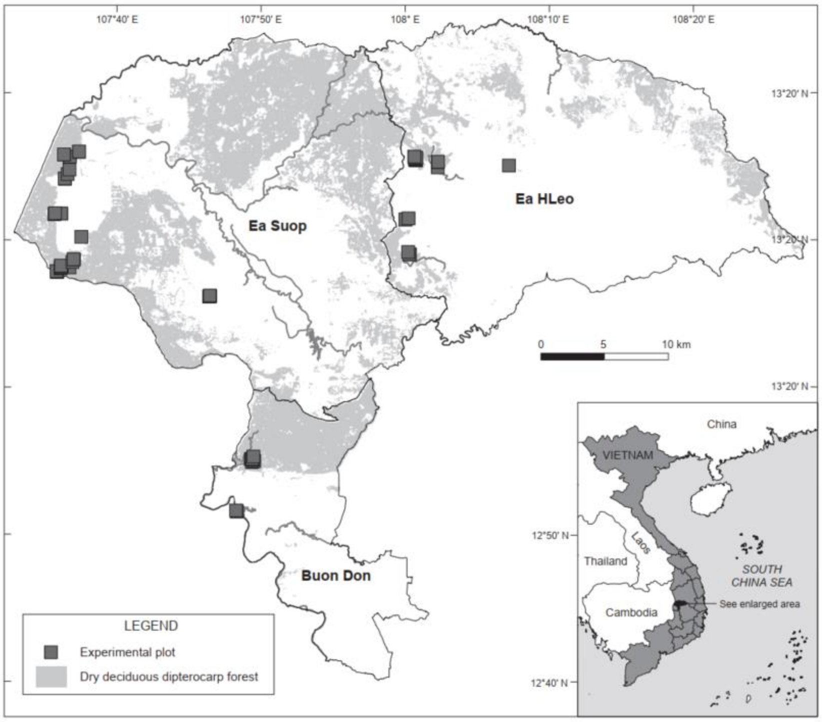

Fig. 1: Location of experimental plots in degraded dry deciduous dipterocarp forest in the Central Highlands, Viet Nam

The study sites were located in two different relatively flat sub-ecoregions at an altitude of 150 m and 450 m, respectively. Mean annual rainfall was 1600- and 1900-mm y^{-1} at the two sites, respectively. The mean annual temperature was 23.0 °C and 25.5 °C, respectively. There were 4–5 months of drought and forest fires at each site annually (Hydrometeorology Stations in Buon Don and Ea Hleo Districts, Vietnam, 2014). Some areas of the study sites were waterlogged or flooded during the rainy season. The soils were formed from four types of bedrocks: shale, basalt, acid magma and sandstone. The range of soil depths varied from <30 cm to >50 cm. The soil surface contained many rocks and stones, and soil nutrient composition varied greatly.

The tree species we used to enrich the degraded DDDF was teak, which belongs to the family Lamiaceae. Teak was planted as 1-year-old stumps (seedlings) with a root collar diameter of 1.0–1.5 cm and a length of 15–20 cm.

2. Experimental design

A set of 64 experiment plots were set up for testing forest enrichment in the Central Highlands (Figure 1). Each plot area was 4900 m^2 (70 m × 70 m) with various combinations of the two groups of factors: ecological conditions (eight factors) and forest status (seven factors). Thus, there was a total of 15 factors, and for each factor at least 2–3 experimental plots were established.

Teak was planted in all forest canopy gaps as long as the minimum distance between each seedling was 3 m, and the distance from each natural tree with diameter at breast height (DBH) > 10 cm was ≥3 m (Figure 2). Therefore, depending on forest density, an average of 263 teak trees were planted in each plot (the minimum was 88 and the maximum was 482). We weeded around and pruned planted teak trees twice per year during the rainy season in June and September. The purpose of pruning was to produce good-quality stems for harvesting and to increase the annual incremental growth in diameter and height (Roshetko et al. 2013). After weeding and plowing, we spread fertilisers on the ground around each teak tree once a year in June, using 0.3 kg lime and 0.15 kg NPK (16:16:8) fertiliser for each tree. We also prevented fires by weeding and burning grasses and small bamboo twice per year at the beginning and the middle of the dry season.

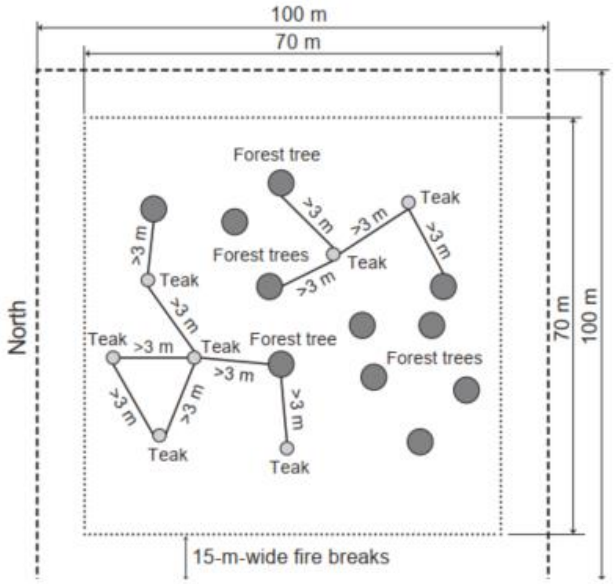

Figure 2: Design of experimental plot of 4 900 m^2 (70 m × 70 m) for enrichment planting of teak in degraded dry deciduous dipterocarp forest. Large circles indicate natural trees of the forest; small circles indicate teak trees that were planted

3. Data collection

Teak trees were planted in the experimental plots twice, in June 2010 and June 2011. We collected data every year in November and December and the final data were collected in December 2015. Data was then updated from 2016 to 2019. We measured height (H; cm) using a measuring tape, diameter at the root collar (D; mm), and diameter at breast height (DBH; mm; if applicable) using an electronic calliper to 0.1 mm. We counted the number of dead trees each year. We measured eight variables in each experimental plot, namely (1) altitude, (2) topography, (3) slope, (4) soil type according to a GIS map (Fischer et al. 2008), (5) soil depth (by drilling), (6) whether an area was submerged during the rainy season, (7) the degree of stone coverage, and (8) the degree of rock coverage. Stone and rock coverages were measured using two diagonal lines (14.14 m for each line) on one 10 m × 10 m subplot for each experimental plot; subplots were located in areas with average stone and rock coverages. We collected data on forest status for seven variables, namely (1) the presence of *Dillenia hookeri* Pierre or *Holarrhena curtisii* King & Gamble, which indicated waterlogging, (2) *Eupatorium odoratum* L., which indicated good growth potential for teak, (3) canopy cover (%) on two diagonal lines of one 10 m × 10 m subplot for each experimental plot each subplot was located where there was average canopy cover), (4) k-tree sampling (k = 6), in which the six nearest trees from a sample point were used as sample trees in each experimental plot (Kleinn and Vilcko 2006) to determine basal area (BA; m^2 ha^{-1}), (5) dominant tree species, (6) tree density (N; trees ha^{-1}); and (7) standing volume (V; m^3 ha^{-1}).

4. Soil sampling and analysis

Three soil samples (0.5 kg each) were collected at a depth of 0–30 cm at three locations per plot (on a diagonal line (14.14 m) across a 10 m × 10 m subplot, at the beginning, middle and end of the diagonal line). Four soil physical indicators were analysed, namely the proportions of clay (%), loam (%), sand (%) and gravel (%) in the soil (Robinson method; Olmstead et al. 1930). We also analysed eight soil chemical indicators (Pansu and Gautheyrou 2003; Huang et al. 2012): pH_{KCl} (meter method; Huang et al. 2012); N (mg per 100 g soil) (Tyurin and Kononova method; Kononova 1966); P_2O_5 (mg per 100 g soil) (Oniani method; Oniani et al. 1973); K_2O (mg per 100 g soil) (flame photometer method; Estefan et al. 2013); Ca^{2+} (meq/100g soil) and Mg^{2+} (meq per 100 g soil) (Trilon B method; Pansu and Gautheyrou 2003); H^+ (meq per 100 g soil) and Al^{3+} (meq per 100 g soil) (Sokolop method; Đalović et al. 2012).

5. Model fitting and selection

To determine the suitability level of teak trees planted in each experimental plot, we used the site classification equation in Table 1, which provided the average height of teak dominant trees (H_{dom}; m) at stand age (A; years) for teak plantations in the Central Highlands. The dominant teak trees were defined as the 20% tallest trees in the stand (Huy et al. 1998). The H_{dom} values (Table 2) for different ages (A) at each site were extracted from the equations listed in Table 1. The values in Table 2 were used to identify planted teak suitability levels by using H_{dom} per Age.

We modelled teak growth as a power function:

$$Y_1 = a \times X^b + \varepsilon \qquad (1)$$

where Y_1 is H_{dom}, or the average height of planted trees (H; m), or the average diameter at the root collar (D; cm) of planted teak trees; and X is the age of the planted teak (years).
We modelled the suitability of teak to determine the important factors affecting the suitability of teak in enrichment planting using the following power function:

$$Y_2 = a \times X_i^{bi} + \varepsilon \qquad (2)$$

where Y_2 is the suitability level of teak, coded as 1 = Very Good, 2 = Good, 3 = Average, 4 = Poor; and X_i are values or codes of ecological conditions that included soil physicochemical properties and forest status. The study analysed the effects of factors on the suitability levels of teak: ecological conditions (eight variables), which included 12 other variables of soil physicochemical properties, and forest status (seven variables). A summary of the ecological conditions and forest status of the experimental plots is shown in Table 3.

Table 1: Parameters a and b of the equation $H_{dom} = a \times \exp(-b \times A^{-0.796})$ for different site classes of the teak plantation in the Central Highlands, Viet Nam. Source: Huy et al. (1998). H_{dom} = average height (m) of dominant trees, defined as the 20% tallest trees in the stand; A = age (years) of the planted teak tree. Upper and lower = respective maximum and minimum value of parameters for each class

Site classes	Parameters changed by site classes	
	a	b
Upper	32.028	3.535
1: Very good	30.439	3.665
Upper	28.859	3.816
2: Good	27.289	3.994
Upper	25.732	4.207
3: Average	24.195	4.466
Lower	22.685	4.789

Table 2: Values of H_{dom} (m) versus Age (year) for different suitability levels of planted teak. Source: Huy et al. (1998). H_{dom} = average height (m) of dominant trees, defined as the 20% tallest trees in the stand; A = age (years) of the planted teak tree. Upper = maximum H_{dom} for each suitability level

	H_{dom} (m) per A (year)			
Suitability level and code	2	3	4	5
Upper	4.2	7.3	9.9	12.0
1: Very good	3.7	6.6	9.0	11.0
Upper	3.2	5.9	8.1	10.0
2: Good	2.7	5.2	7.3	9.0
Upper	2.3	4.5	6.4	8.0
3: Average	1.8	3.8	5.5	7.0
Upper	1.4	3.1	4.6	6.0
4: Poor	Below average suitability level			

Mallows's (1973) C_P was used to select the X_i factors to use in the model, where a C_P value close to the number of variables P indicated the number of important factors.

Modelling was performed by weighted, non-linear, multivariate regression (Saint-André et al. 2005; Picard et al. 2012). The weight variable = $1/X_i^a$, where X_i was the key independent variable and parameter a ranged from -20 to +20; the value of a was changed to obtain statistical indicators of the optimal model.

The best models were determined as those with significant parameters that had no obvious issues with diagnostic plots, the lowest mean absolute error (MAE), lowest mean absolute percent error (MAPE%) (Mayer and Butler 1993), and high adjusted R^2 (R^2_{adj}).

Table 3: Summary of ecological conditions and forest status of the experimental plots

Factors	Min	Average	Max	Standard Deviation
Ecological sites:				
Altitude (m)	157	208	466	55.0
Topography	Flat - Slope - Top			
Slope (degree)	0	1.7	17	3.7
Soil type	Stagni-Arenic Fluvisols, Hyperskeletic Leptosol, Dystri-Plinthic Planosols, Endoleptic Luvisols, Geri-Acric Ferralsols, Geri-Acric Ferralsols, Hapli - Arenic Lixisols, Arenic Acrisols, Endoskeleti-Arenic Luvisols, Eutri-Anthraquic Planosols, Endoleptic Acrisols, Epileptic Acrisols, Episkeletic Acrisols, Endoleptic Lixisols.			
Soil depth (cm)	< 30 cm, 30 - 50 cm, > 50cm			
Waterlogging in rainy season	Yes or No			
Stone coverage (%)	0	11.5	90.0	25.0
Rocks coverage (%)	0	10.6	64.0	19.8
Forest status:				
Canopy cover (%)	10	33.1	78.0	17.4
Basal Area (BA, m^2 ha^{-1})	1.0	7.6	24.2	4.8
Tree density with DBH ≥10cm (N, tree ha^{-1})	48	214	558	128
Stand volume (V, m^3 ha^{-1})	3.7	40.2	198.3	30.7
Dominant tree species	*Dipterocarpus tuberculatus* Roxb., *Terminalia alata* Wall., *Shorea obtusa* Wall. Ex Blume, *Shorea siamensis* (Miq.) Kurz, *Dipterocarpus obtusifolius* Teijsm. ex Miq., *Xylia xylocarpa* (Roxb.) Taub., *Terminalia chebula* Retz.			

$$MAE = \frac{1}{n}\sum_{i=1}^{n} /\hat{Y}_i - Y_i / \quad (3)$$

$$MAPE\% = \frac{100}{n}\sum_{i=1}^{n} \frac{/\hat{Y}_i - Y_i /}{Y_i} \quad (4)$$

where $\hat{Y}_i$ is the predicted value, Y_i is the observed value, and n = number of experimental plots or number of trees.

Results

1. Suitability of teak in dry deciduous dipterocarp forest

The suitability of teak was determined at four levels: Very Good (4/64 plots, 6.3%), Good (5/64 plots, 7.8%), Average (18/64 plots, 28.1%), and Poor (37/64 plots, 57.8%) (Figure 3). At the age of 4 years, H_{dom} attained 11.2, 7.8, 5.3 and 3.8 m for the respective suitability levels in the order from Very Good to Poor (Table 4). These results demonstrated that teak shows high potential for enrichment planting in degraded DDDF; 42% (27 out of 64) of the experimental plots had suitability levels of Average to Very Good. The survival rates of the planted teak trees were also high. At the suitability levels of Average, Good and Very Good, the survival rates were in the range of 89–98%. At the Poor suitability level, the survival rate was 74%.

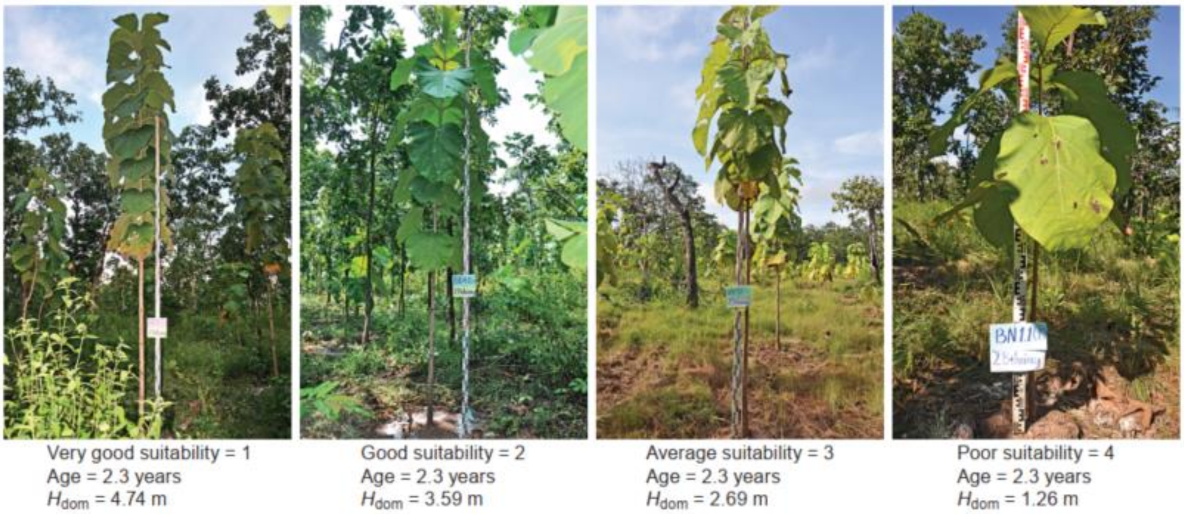

Fig. 3: Dominant trees of teak, defined as the 20% tallest trees in the stand at four different suitability levels

2. Growth of teak at four suitability levels

The growth in H_{dom}, and the average growth of H and D of planted teak were modelled by a power function (Table 5, Figure 4). The growth in H_{dom}, H and D of planted teak in the DDDF fitted by the power function with $R^2_{adj.}$ ranged from 70% to >90%. All models had MAPE% < 23%. Based on the fitted models, the increases in H_{dom}, H and D versus age (A) for each suitability level were determined (Table 6). At 4 years old, planted teak trees in degraded DDDF at the suitability levels Very Good, Good, Average and Poor had average heights of 8.0, 4.9, 3.0 and 1.9 m, respectively, and average root collar diameters of 8.5, 6.5, 5.2 and 4.2 m, respectively. Height increased from 0.5 to 2.0 m y^{-1} in stands of suitability levels from poor to very good.

Table 4: Average growth and survival rate of teak at four suitability levels at the age of 4 years. H_{dom} = average height (m) of dominant trees, defined as the 20% tallest trees in the experimental plot; H = average height (m) of planted teak trees; D = average root collar diameter (cm) of planted teak trees

Suitability level	H_{dom} (m)	H (m)	D (cm)	Survival rate (%)
Very good	11.2	8.0	8.5	98
Good	7.8	4.9	6.5	92
Average	5.3	3.0	5.2	89
Poor	3.8	1.9	4.2	74

Table 5: Models of the average growth of planted teak trees at four suitability levels. A = age (years) of the planted teak tree; H_{dom} = average height (m) of dominant teak trees, defined as the 20% tallest trees in the experimental plot; H = average height (m) of planted teak trees; D = average root collar diameter (cm) of planted teak trees; MAE = mean absolute error; MAPE = mean absolute percent error

Suitability level	Model	No. of plots	R^2 adj. (%)	Weight variable	MAE	MAPE (%)
Very good	$H_{dom} = 1.36195 \times A^{1.51869}$	8	78.30	1/A	0.49	16.13
	$H = 0.83781 \times A^{1.62705}$	8	80.59	$1/A^{2.0}$	0.28	15.69
	$D = 2.73870 \times A^{0.81786}$	8	68.14	1/A	0.40	9.59
Good	$H_{dom} = 1.09024 \times A^{1.42026}$	10	82.70	1/A	0.36	14.72
	$H = 0.59138 \times A^{1.52806}$	10	87.01	$1/A^{3.0}$	0.13	9.35
	$D = 2.09944 \times A^{0.81261}$	10	91,37	$1/A^{-0.5}$	0.18	5.03
Average	$H_{dom} = 0.70281 \times A^{1.45364}$	36	75.90	$1/A^{0.50}$	0.29	17.15
	$H = 0.40408 \times A^{1.44874}$	36	82.50	$1/A^{1.0}$	0.14	15.40
	$D = 1.67369 \times A^{0.82276}$	36	71.69	$1/A^{0.5}$	0.33	12.76
Poor	$H_{dom} = 0.18434 \times A^{2.18043}$	74	79.52	$1/A^{-8.0}$	0.41	16.55
	$H = 0.23426 \times A^{1.50170}$	74	75.61	$1/A^{1.5}$	0.15	22.07
	$D = 0.93983 \times A^{1.07353}$	74	74.48	$1/A^{-2.0}$	0.36	14.09

3. Factors affecting the suitability levels of planted teak

The best model included six variables to predict suitability levels of teak, with Mallows's CP value close to six and the $R^2_{adj.}$ attained the highest value. The modelling results identified six key variables (altitude, volume, soil type, waterlogging, percentage sand, and concentration of P_2O_5) that affected the suitability levels of teak planted in the experimental plots, according to the following model:

$$\textit{Suitability Level} = \textit{Waterlogging} \times 0.105505 \times (\textit{Altitude} \times \textit{Volume})^{-0.09507} \times \textit{Soil Type}^{-0,27482} \times \textit{Sand}^{0.93701} \times P_2O_5^{-0.19901} \quad (5)$$

Statistical indicators of the fitted model (Equation 5) were number of plots = 64, p-value of all parameters < 0.05, $R^2_{adj.}$ = 82.18%, weight variable = $1/Sand^7$, MAE = 0.22 and MAPE = 12.98% and the six parameters had p-values much less than 0.05. These indicators showed a strong relationship between the suitability of planted teak under different DDDF conditions and the six factors in the fitted model (Equation 5).

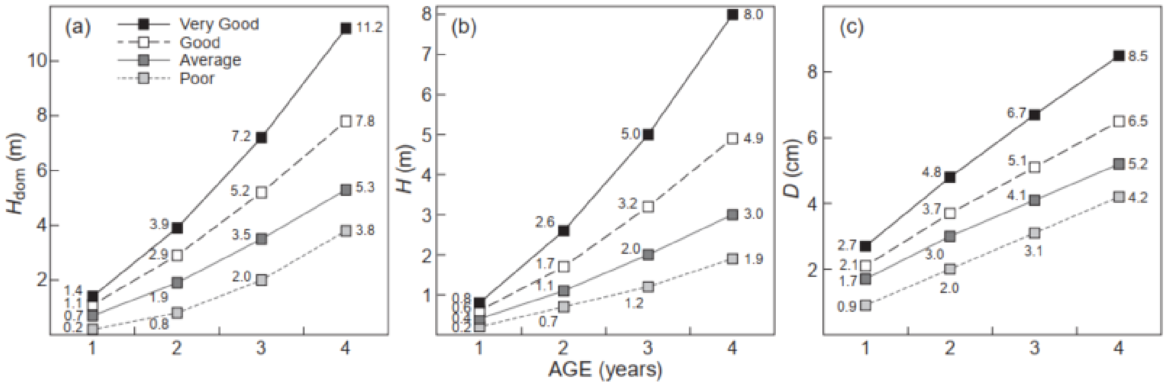

Fig. 4: Average growth of planted teak versus age (in years) at four different suitability levels fitted by a power equation. (a) Average height (H_{dom}; m) of dominant teak trees, defined as the 20% tallest trees in the experimental plot; (b) average height (H; m) of teak trees; (c) average root collar diameter (D; cm) of teak trees

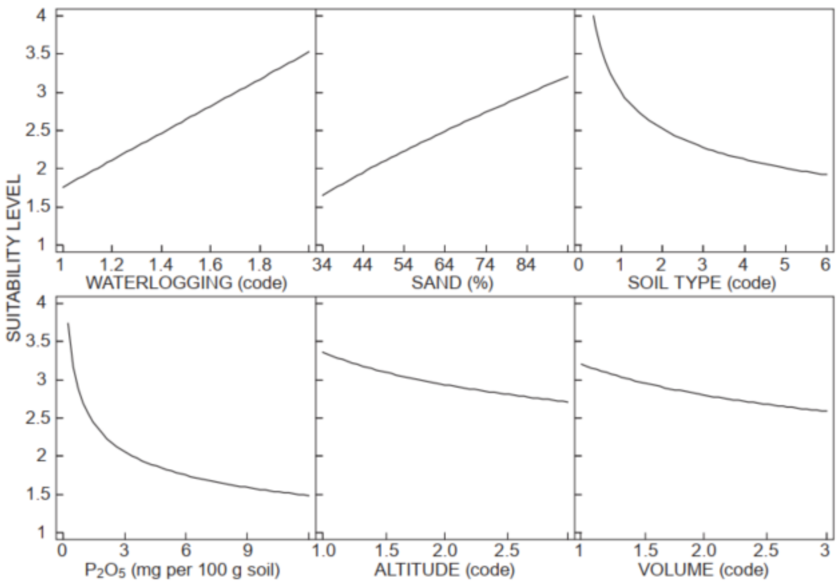

Fig. 5: Fitted suitability level versus each key variable that affects the suitability levels of teak planted in dry deciduous dipterocarp forest

In Equation 5, the variables have codes or values as follows: (1) suitability level of teak: 1 = Very Good, 2 = Good, 3 = Average, 4 = Poor; (2) waterlogging in the rainy season: 1 = no, 2 = yes; (3) altitude: 1 = 300–400 m, 2 = 100–200 m, 3 = 200–300 m; (4) volume (stand volume of the dipterocarp forest): 1 = 100–150 $m^3 ha^{-1}$, 2 = <50 and >150 $m^3 ha^{-1}$, 3 = 50–100 $m^3 ha^{-1}$; (5) soil type: 1 = StagniArenic Fluvisols, Hyperskeletic Leptosol, 2 = Dystri-Plinthic Planosols, Endoleptic Luvisols, Geri-Acric Ferralsols, Geri-Acric Ferralsols, Hapli-Arenic Lixisols, Arenic Acrisols, 3 = Endoskeleti-Arenic Luvisols, Eutri-Anthraquic Planosols, 4 = Endoleptic Acrisols, Epileptic Acrisols, 5 = Episkeletic

Acrisols, 6 = Endoleptic Lixisols; (6) sand: percentage sand in the soil, values ranged from 34% to 85%; and (7) P_2O_5: concentration in the soil, values ranged from 1.6 to 10.6 mg per 100 g soil. Figure 5 demonstrates trends of suitability level of teak planted in DDDF versus each key variable.

Table 6: Growth and increment of the height and root collar diameter of planted teak trees at four suitability levels. A = age (years) of the planted teak tree; H_{dom} = average height (m) of dominant teak trees, defined as the 20% tallest trees in the experimental plot; H = average height (m) of planted teak trees; D = average root collar diameter (cm) of planted teak trees; ΔH = mean increment in average height of planted teak trees (m y^{-1}); ΔD = mean increment in average root collar diameter of planted teak trees (cm y^{-1})

Suitability level	A (y)	H_{dom} (m)	H (m)	D (cm)	Δ_H (m/y^{-1})	Δ_D (cm/y^{-1})
Very good	1	1.4	0.8	2.7	0.8	2.7
	2	3.9	2.6	4.8	1.3	2.4
	3	7.2	5.0	6.7	1.7	2.2
	4	11.2	8.0	8.5	2.0	2.1
Good	1	1.1	0.6	2.1	0.6	2.1
	2	2.9	1.7	3.7	0.9	1.8
	3	5.2	3.2	5.1	1.1	1.7
	4	7.8	4.9	6.5	1.2	1.6
Average	1	0.7	0.4	1.7	0.4	1.7
	2	1.9	1.1	3.0	0.6	1.5
	3	3.5	2.0	4.1	0.7	1.4
	4	5.3	3.0	5.2	0.8	1.3
Poor	1	0.2	0.2	0.9	0.2	0.9
	2	0.8	0.7	2.0	0.3	1.0
	3	2.0	1.2	3.1	0.4	1.0
	4	3.8	1.9	4.2	0.5	1.0

We can use the fitted model (Equation 5) to predict the suitability of teak in a specific DDDF site. Table 7 gives examples of variable values that would give each of the four possible suitability levels.

Discussion

1. Suitability of planted teak in different dry deciduous dipterocarp forest sites in initial stage

In this study, the enrichment planting using teak in degraded DDDF showed the ability of the trees to adapt to the same four site classes that are seen in teak plantations (Huy et al. 1998). This finding is important because it is challenging to find non-dipterocarp species that can adapt well to the extreme sites in degraded DDDF. In fact, it has been difficult to find timber species of high economic value that have the ability to adapt to the extreme conditions of DDDF, such as forest fires, droughts, waterlogging and rocky soils. One reason that may explain why teak is able to survive dry conditions is that they are deciduous and drop their leaves during the dry season. Teak is also a fire-resistant species owing to its thick bark, which allows the trees to withstand extreme droughts and wildfires in dipterocarp forests where there is low rainfall during the dry season for 4–5 months each year (Ladrach 2009). In Myanmar, teak is associated with DDDFs that are dominated by *Dipterocarpus, Shorea, Terminalia* and *Pentacme* species (Weaver 1993).

Table 7: Examples of values of six key variables for four suitability levels

Variable	Suitability level			
	Very good	**Good**	**Average**	**Poor**
Altitude (m)	200 – 300	300 – 400	100 – 200	300 – 400
Volume (m^3/ha)	50 – 100	100 – 150	> 150	100 – 150
Soil Type	Endoskeleti or Arenic Luvisols	Endoskeleti or Arenic Luvisols	Endoleptic Acrisols or Epileptic Acrisols	Stagni-Arenic Fluvisols or Hyperskeletic Leptosol
Waterlogging	No	No	No	Yes
Sand (%)	< 43	43 - 60	61 - 77	61 - 77
P_2O_5 (mg per 100 g soil)	> 9.0	> 9.0	6.1 – 9.0	3.0 – 6.0

Teak has been used successfully in agroforestry and forest enrichment systems. Enrichment planting of teak is the main method for filling canopy gaps in tropical moist forests of the Andaman Islands (Weaver 1993). In northern Laos, teak is a key timber species for smallholder farming systems that attempt to diversify farm products. Teak-based systems helped farmers convert from slash-and-burn agriculture to a system that allows tree cover to re-establish (Roshetko et al. 2013). As a result, teak can be used to rehabilitate degraded forests after slash-and-burn, and it can be used to rehabilitate over-logged forests.

Enrichment planting has been a silvicultural intervention in DDDF management, and several dipterocarp species have been planted successfully in natural forests (Barnard 1954 and Tang and Wadley 1976, cited by Appanah 1998); teak planting has been successful in Karnataka and several other Indian states, and in Sri Lanka. Some studies of silviculture techniques have used *Shorea* species for enrichment planting of dipterocarps in over-logged, secondary forests (Adjers et al. 1995). Wyatt-Smith (1963) pinpointed the conditions that merit enrichment planting (i.e. that species should produce timber of high value). The present study is the first to demonstrate the potential of using teak for enrichment planting in degraded DDDF in Viet Nam. The results of this study may also be applicable in neighbouring countries, such as Cambodia, Laos and Thailand, that have DDDFs in similar ecological conditions.

2. Growth rate of planted teak during the first 5 years in dry deciduous dipterocarp forest

At the age of 5 years, the top tree heights for teak plantations in Costa Rica ranged from 13 to 15 m (Bermejo et al. 2004). The site classification for teak in the Caribbean Basin based on mean top height of the 100 largest-diameter trees per hectare showed that the mean top height at the age of 4 years was 4–11 m (Weaver 1993). In the present study, at 4 years old the H_{dom} values of teak were 3.8–11.2 m achieved from Poor to Very Good suitability levels. Normally, teak is planted in appropriate soils in mono-plantations or following agroforestry practices. According to an ICRAF (2010) review and Pérez and Kanninen (2005) in Costa Rica, the annual increment of plantation teak in advantageous conditions at the age of 5 years is 2 m in height and 2 cm in diameter. Bisaria et al. (2014) observed that the mean annual height growth rate in teak plantations was 1.7 m y^{-1} after 11 years. In the current study, the annual increment of teak at the Very Good suitability level at the age of 4 years was 2 m in height and 2 cm in diameter (Table 6). Therefore, this suitability level is highly appropriate for enrichment planting in degraded DDDF.

Annual increments in height and diameter were 1.2 m and 1.6 cm, respectively, for the Good suitability level, which were slightly lower compared with growth rates achieved in teak plantations. The increments at the Average and Poor suitability levels were even lower. Therefore, DDDF areas predicted to having low suitable levels (Average or Poor) are not recommended for enrichment planting with teak.

In the present experiment, the practical goal is to produce small saw logs that are around 15 cm in diameter with an expected harvesting cycle of 20–25 years (Huy et al. 1998; Roshetko et al. 2013). Continued monitoring of the experimental plots for at least another 10–15 years is needed. More intensive silvicultural practices would increase the increment of planted teak and generate large, higher-quality timber. Roshetko et al. (2013) stated that over a two-year period, thinning and pruning treatment increased incremental DBH by 60% and incremental tree height by 124%.

3. Factors that affect growth and suitability of planted teak in different dry deciduous dipterocarp forest sites

The growth increments during the initial establishment of teak planted in the DDDF were sensitive to variation among ecological conditions and forest status factors. Analysis of the fitting model (Equation 5) for six key factors indicated the following: (1) soil types highly suitable for teak growth were Endoleptic Acrisols, Epileptic Acrisols, Episkeletic Acrisols and Endoleptic Lixisols. This finding is consistent with the existing knowledge that teak is capable of growing on a variety of soil types (Kaosa-ard 1998). (2) An altitude range of 200–300 m was favourable for teak. This shows that altitude is a limiting factor in enriching DDDF with teak. (3) Where the forests were not waterlogged, all four suitability levels of teak were observed. With slight waterlogging, the suitability level was only from Average to Poor. This is consistent with Kaosa-ard (1998) and Ladrach (2009), who showed that teak requires well-drained soils. A global overview conducted by Pandey and Brown (2000) showed that the best teak forests, both natural and plantation, grew in well-drained deep alluvium soils. (4) Well-suitable teak in DDDF had a stand volume ranging from 50 to 100 m^3 ha^{-1}, and poorly suitable teak in DDDF had a stand volume of 100–150 m^3 ha^{-1}. Forest stand volume shows a relationship with the forest canopy and light intensity under the canopy. Chowdhury et al. (2008) reported that teak does not grow well in low-light conditions, but regenerated shoots under an open canopy grew well. Teak planting should be applied in degraded DDDFs that have a stand volume lower than 100 m^3 ha^{-1}. (5) The percentage sand in the soil significantly influenced the suitability levels of teak. The increase in percentage sand of the soil reduced the suitability. This finding is also consistent with some previous studies. Kaosa-ard (1998) observed that teak showed poor growth on dry sandy soils; Ladrach (2009) concluded that teak grows best on loam to clay-loam soils and does not grow well on excessively drained sands. (6) Increasing the content of P_2O_5 in forest soils helped promote the growth of teak. This finding confirmed that teak has a high requirement for calcium and phosphorus (Bhatia 1954; Seth and Yadav 1958, cited by Kaosa-ard 1998; Rugmini et al. 2007; Ladrach 2009). Our finding was also consistent with the review by Weaver (1993), which indicated that teak trees are sensitive to phosphate deficiency.

Conclusions

We determined four suitability levels for enrichment planting with teak in degraded DDDF in the Central Highlands of Viet Nam. Survival rates of teak trees at the Average to Very Good suitability levels were greater than 90%. The growth and increment of planted teak in DDDF at the Very Good suitability level produced higher growth rates, whereas at the Good suitability level growth rates were slightly lower compared with those of prime sites for teak plantations during the first 5 years after planting. Enrichment planting with teak in degraded DDDF is recommended for forest areas that are of Very Good and Good suitability levels.

Teak has been planted widely and successfully in its native range and in many other tropical countries, primarily in plantations. This study showed that teak is also a potential tree species for use in enrichment planting in degraded DDDFs that experience extreme ecological conditions, such as long periods of drought in the dry season and waterlogging or flooding in the rainy season. Enrichment planting with teak will improve the economic value of degraded DDDF and help to reduce the conversion of degraded DDDF to other types of land use, thus preventing deforestation.

We identified six key factors that affected the suitability of teak as an enrichment tree for degraded DDDF in the Central Highlands of Vietnam. These factors include waterlogging, altitude, forest stand volume, soil type, percentage sand, and P_2O_5 concentration in the soil. These factors can be used to classify degraded forest areas that are more suitable for enrichment planting with teak.

This study was conducted in only 5 years with a commercial goal of planting teak for small saw logs that are about 15 cm in diameter and an expected harvesting cycle of approximately 20–25 years. We recommend that teak growth monitoring should be continued in order to collect additional data for validation of the models developed in this study, leading to a more complete assessment of the potential of using teak in enrichment planting in DDDF.

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