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Growth prediction for rubber tree and intercropped forest trees to facilitate environmental services valuation in South Thailand

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Abstract. *Nattharom N, Roongtawanreongsri S, Bumrungsri S. 2020. Growth prediction for rubber trees and intercropped forest trees to facilitate environmental services valuation in South Thailand. Biodiversitas 21: 2019-2034.* Tree growth parameters are necessary for valuing ecological services of trees in both natural forest and agroforest. These parameters are difficult to measure annually, and thus often lack the information needed in valuation. This study aimed to use regression analysis to create growth models for diameter at breast height (DBH), total height (TH), and merchantable height (MH) of *Hevea brasiliensis* Mull-Arg. (rubber tree) and five economic forest trees that are preferred by rubber farmers for intercropping, including *Hopea odorata* Roxb., *Shorea roxburghii* G.Don., *Swietenia macrophylla* King., *Dipterocarpus alatus* Roxb., and *Azadirachta excelsa* (Jack) Jacobs. Data were collected from 39 rubber plantations that contain rubber trees and the intercropped tree species at different ages in three provinces in South Thailand. The data were modelled using regression analysis with curve fitting to find the best-fitted curve to a given set of points by minimizing the sum of the squares of the residuals and standard error of the regression of the points from the curve. The results arrived at 21 models for the DBH, TH, and MH growth of rubber and the intercropped trees, in the forms of, power, sigmoid and exponential trends that vary according to the type of trees. The models can be used to predict tree growth parameters, which are useful for determining the value of ecosystem services such as carbon dioxide sequestration, oxygen production, and timber production.

Keywords: Agroforest, ecosystem services, economic valuation, modelling tree growth, rubber and intercropping

Abbreviations: DBH: diameter at breast height, TH: total height, MH: merchantable height

INTRODUCTION

In southern Thailand, rubber (*Hevea brasiliensis* Mull-Arg.) has been one of the most intensive commercial crops following the national policy to increase both yield and growth of the industry since 1960 (Rubber Authority of Thailand 2012). Recently, the global environmental movement has influenced many agencies, through projects such as Tree Bank (Bank for Agriculture and Agricultural Cooperatives 2015), Economic Forest Trees Planting Promotion Project for Economy, and the Society and Environmental Sustainability (Ministry of Natural Resources and Environment 2018), to encourage monoculture rubber farmers to diversify crop plants and thus alleviate climate change and improve ecosystems. One such approach is to adopt an agroforestry practice by intercropping rubber with other trees, aiming to increase diversity in the plantation. Adding intercropping to the rubber plantations can increase the potential for absorbing carbon from the atmosphere and storing it in different parts of the trees (Bumrungsri et al. 2011; Kumar and Nair 2011; Kittitornkool et al. 2014). It can improve the ecosystems, particularly by preventing soil erosion. The complexity of canopy between *H. brasiliensis* and intercropping helps reduce run-off (Witthawatchutikul 1993), while the complexity of root systems also helps the soil surface to adhere (Wibawa et al. 2007; Kittitornkool et al. 2014) and the high litterfalls in this plantation can increase nutrients in the soil (Wibawa et al. 2007; Bumrungsriet al. 2011). Often, the government supported the intercropping by supplying seedlings of forest trees of economic value such as *Hopea odorata* Roxb. (takhian thong), *Shorea roxburghii* G.Don. (payom), *Swietenia macrophylla* King. (mahogany), *Dipterocarpus alatus* Roxb. (yang-na), and *Azadirachta excelsa* (Jack) Jacobs. (sadao-thiam) (Ministry of Natural Resources and Environment 2018). These species thus become the popular choices for rubber farmers as they serve the dual purposes of increasing additional income as well as increased ecosystem services (Kittitornkool et al. 2014). However, not much is known about how this adoption genuinely generates the overall ecosystem services to the local ecosystem. The research found in Thailand limited to studying trees' carbon storage at certain ages. For example, Bumrungsri et al. (2011) studied the carbon storage in 45-years-old agroforest rubber plantation and 15-years-old monoculture rubber plantation in Phatthalung province. Poosaksai et al. (2018) studied the carbon storage of *Pterocarpus macrocarpus* Kurz, *H. odorata, Azadirachta indica* A. Juss and *A. excelsa* aged 21 years old at Prachuap Khiri Khan province. To our knowledge, no study provides information for continual estimation.

Recognition of ecosystem service value in terms of the monetary unit helps to make better decisions in allocating limited resources efficiently (Barbier et al. 2009). In forest and agroforest ecosystems, a variety of ecosystem services are generated, primarily carbon sequestration, oxygen production (Yolasiğmaz and Keleş 2009), soil erosion protection (Kittitornkool et al. 2014), and microclimate control (Bumrungsri et al. 2011). To value these ecosystem services, tree growth parameters are needed to be quantified before converting to monetary value. These parameters are diameter at breast height (DBH), total height (TH) and merchantable height (MH) (Brown et al. 1989; Takimoto et al. 2008; Bumrungsri et al. 2011; Villeamor et al. 2014). However, annually measuring tree growth parameters is extremely effort demanding (Cao 2004); therefore, the availability of such data is scarce, making it challenging to calculate the economic value. Hence, being able to estimate these parameters at the tree age where the value is accounted would facilitate the economic valuation. Otherwise, the unavailability of this information would limit the accuracy of the economic valuation of the aforementioned ecosystem services.

In southern Thailand, in particular, the climate here is a tropical rainforest climate, with high annual rainfall (Lohmann et al., 1993). This condition generally results in trees in this region having a larger size than other areas in Thailand of the same age, particularly *H. brasiliensis* (Rubber Research Institute of Thailand 2018). That is because the climate influences the growth of the tree (Toledo et al. 2011; Ciceu et al. 2020). Thus, tree growth parameters from different regions or climates may underestimate the values of ecosystem services in the southern region. Furthermore, most of the research on tree growth in Thailand often uses data from experimental fields. The species of intercropped trees in the actual plantations have not yet been studied to cover the DBH, TH, and MH. The results of the research, for example, by Sathapong (1970) and Sakai et al. (2010), were usually reported as raw data, without any attempt to create a model to predict tree growth for aiding economic valuation.

In order to overcome such an obstacle, it is necessary to be able to forecast the tree growth parameters at any particular age. Tree growth usually depends on their growth rate, which in turn often relates to tree age. Thus, if the growth rate can be determined, the tree growth parameters at a particular age can then be estimated. One approach is, therefore, to generate a regression model using the relationship between the growth rate and the age of the tree to forecast the DBH, TH, and MH. Current literature shows that research on the growth rate of a rubber tree and particular economic forest trees favored by rubber farmers in southern Thailand is lacking. In other words, there are no specific models to estimate the tree growth parameters of those trees at a particular age. Three studies in different regions of Thailand reported the growth in the form of diameter, but they did not generate predictive models (Hongthong 1991; Visaratana et al. 1991; Sathapong 1970). These were the studies of the diameter of one-year-old seedlings *Dalbergia cochinchinensis* Pierre, *Afzelia xylocarpa* (Kurz), *D. alatus*, and *H.odorata* under canopy of *Leucaena leucocephala* (Lamk.) De Wit at Nakhon Ratchasima province (Visaratana et al. 1991); the study of DBH and TH of 17-year-old *H. odorata* planted with *Senna siamea* (Lam.) Irwin & Barne and *D. alatus* planted with *L. leucocephala* at Nakhon Ratchasima province (Sakai et al. 2010); and the study of DBH and TH of *S. macrophylla* at Prachuap Khiri Khan province (Sathapong 1970). In the southern region, we found the study of saplings diameter of one-year-old *D. alatus*, *Dipterocarpus gracilis* Blume, *Dipterocarpus dyeri* Pierre ex Laness., *Parashorea stellata* Kurz, *H. odorata* and *Cotylelobium lanceolatum* Craib under canopy of *Acacia auriculiformis* A. Cunn. ex Benth. at Surat Thani (Hongthong 1991) and the DBH study of 4.5 to 9-year-old *S. macrophylla* and *A. excelsa* was planted with *H. brasiliensis* at Songkhla, Krabi and Yala provinces.

This research intended to develop models for predicting DBH, TH, and MH at any particular age for individual rubber trees and rubber farmers' preferred economic forest tree species. Five species of economic trees were *H. odorata, S. roxburghii*, *S. macrophylla*, *D. alatus*, and *A. excelsa* in rubber plantations in southern Thailand. These species of intercropped trees are commonly grown in southern Thailand because of the government's support for the seedlings and techniques for planting these trees and because they are high-value trees. The results of the study can be used to assist in valuing ecosystem services more accurately, which consequently would assist the policymakers. Furthermore, plantation managers and economists can use this information for better farm management.

MATERIALS AND METHODS

Study area

The researchers used a snowballing method from experts who work with rubber farms to identify the rubber farmers who were already intercropping economic trees with rubber. To our knowledge, there were not many rubber farms with intercropped economic forest trees in southern Thailand (Kittitornkool et al. 2014). This situation restricts the number of plots and trees used in this study. The total of such plantations were 39 in Songkhla, Phatthalung, and Trang provinces (5° 57' to 10° 59' N and 98° 11' to 102° 04' E) (Figure 1). Generally, they were a small-scale plantation with the area between 0.48-0.8 ha. The plantations located below 100 m elevations, with the annual rainfall between 1,600- 2,400 mm on average (Climatological Center 2020). Detail of these sites is shown in Table 1. These farms had non-uniform but similar intercropping practices. Usually, intercropped trees were planted when rubber trees reach the age of four. Farmers often planted single or mixed species of economic trees in one row, alternating with rubber trees in several rows. The space between rows of rubber trees was 3 m, and the space between economic trees and rubber trees was 3.5 m. The average number of economic trees was 238 trees ha^{-1} in each plantation, whereas the average number of rubber trees was 475.

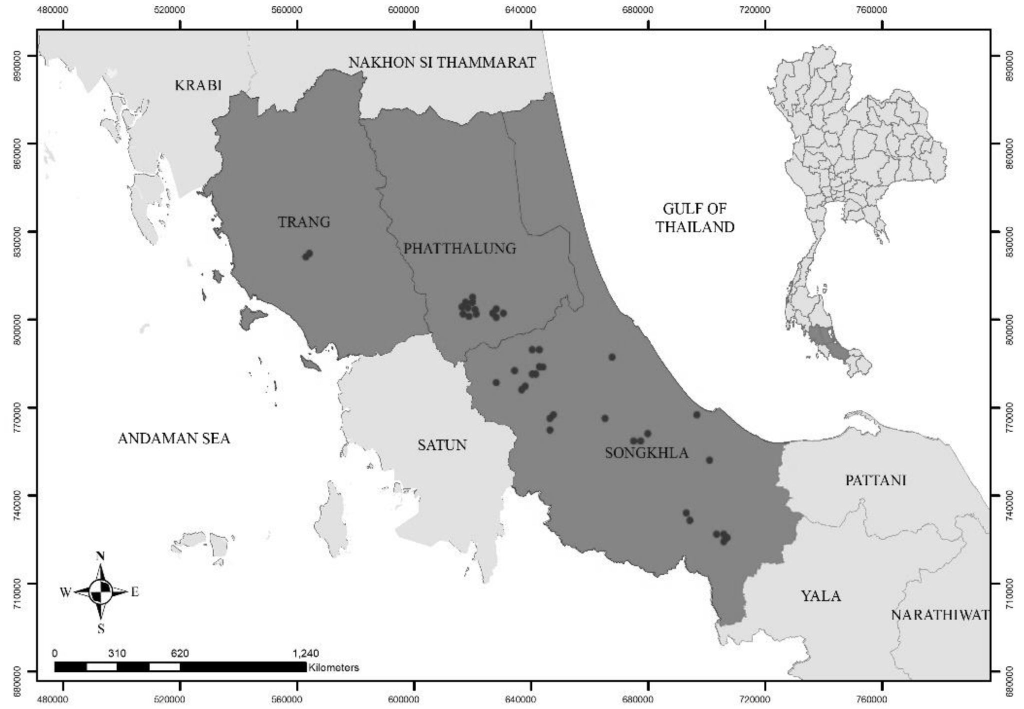

Figure 1. Locations of examined rubber plantations are shown by the black dot

Tree sampling and growth measurement

Trees at different ages were sampled depending on the number of trees in the plantation. If the total number of trees in each species in any plantation was less than 30, all trees were measured for their growth parameters. The figure of 30 is an arbitrary number corresponding to the time limitation of the research. However, if the total number was more than 30, a simple random sampling was used to select the rows of trees. Rows of trees were sampled randomly (using a random number generator app on a mobile phone). Every tree on that row was then measured. The row sampling was repeated until the number of each species sufficed.

DBH was measured using a measurement tape at the 130 cm height. TH and MH measurements were done by using a measuring pole (with the resolution of 0.1 m) if a tree height was below 10 m and a hypsometer (Nikon Forestry Pro, with the resolution of 0.2 m) if a tree height exceeded 10 m. TH is the distance along the axis of the bole of the tree from the ground to the uppermost point (tip), whereas MH is the distance from the base of the tree to the first branching or other defects of the tree (Brack 1999).

Before sampling and measuring the tree size, the farmers who own the plantation were interviewed about the number of trees, age, and planting system of each tree species in the plantation. They were also asked to give observations from their experience on the growth of each tree species.

The number of measured trees

When *H. brasiliensis* is about seven years old, it is a common practice that farmers usually start tapping. The tapping of latex causes the tree to lose carbon which is a structural material and the source of metabolic energy for the growth process (Silpi et al. 2006). Since tapping is known to reduce the tree growth rate (Silpi et al. 2006), *H. brasiliensis* was separated into two groups: the trees before tapping (1-7 years) (140 trees) and the trees after tapping (> 7 years) (725 trees). For intercropped trees, there were *H. odorata* (521 trees), *S. roxburghii* (368 trees), *S. macrophylla* (243 trees), *D. alatus* (194 trees) and *A. excelsa* (131 trees) (Table 2).

Modelling tree growth

A linear regression analysis that is widely used to determine the tree's growth of each species (Linder 1981; Cao 2004; Westfall and Laustsen 2006; Saaludin et al. 2014) and curvilinear regression were used in this study (Gignac 2019). The curve estimation procedure was performed to find the model that best fits the data set. Previous works often suggest different but common types of model for age and growth relationship: linear (Saaludin et al. 2014), logarithm (Tamchai and Suksawang 2017), power (Forestry Research Center 2009), and exponential (Linder, 1981; Devaranavadgi et al. 2013). The models were fitted with these types of model. According to the shape of the scatter plot, the s-curve and growth models were also fitted. The key goodness-of-fit measures include the low standard error of the regression, the low total sum of square, low mean squared residuals, significant regression *p*-value, constant and significant coefficient *p*-values, and plausibly high adjusted R-square (but not necessarily the highest), as well as the non-systematic residuals plot (Wasserman 2004).

RESULTS AND DISCUSSION

Descriptive statistics results of the data

Table 3 shows a summary of the descriptive statistics of the data of each species. Since the data set comprised trees from different ages from different plantations that may not start planting in the same year, the growth parameters were expected to show a wide range of variability. Few farmers started planting intercropped trees 20-30 years back; naturally, there were fewer numbers of older trees in the data set. This fact contributed to the data being scattered more in the younger years than the older years, thus giving the data a positive skew. Exceptions were found for the TH and MH of *H. brasiliensis* before tapping and *A. excelsa*, for which the data were slightly negatively skewed. The scatter plot and skewness of the data indicated that linear regression might not represent the best fit line; thus, curvilinear regression was performed.

The regression models

The results showed 21 models of the relationship between age and DBH, TH and MH of the six species (Table 4 and Figure 2-4). For *H. brasiliensis*, the relationships between age and DBH, TH, and MH before and after tapping yielded similar patterns: power for DBH and TH, and exponential for MH. The goodness-of-fit parameters of the MH models did not differ much between power and exponential functions: i.e., for the *H. brasiliensis* before tapping, the standard error of the estimate for power and exponential functions were .192 and .190, and the MSE .037 and .036, respectively (Table 5). Therefore, either function could be selected. The same pattern was found for *H. brasiliensis* after tapping too. However, the model with the lowest statistical measures of the goodness-of-fit was chosen as a predictive model. For *H. odorata, S. macrophylla, and D. alatus*, the relationships were all in the form of exponential across all growth parameters. For *S. roxburghii,* the DBH took a power function while the TH and MH took exponential functions. All relationships between age and tree growth of *A. excelsa* were Sigmoid.

The implication for economic valuation

The ecosystem services from the forest, particularly carbon dioxide sequestration, oxygen production, and timber provisioning service, require the parameters of growth size. For instance, to calculate carbon dioxide sequestration, the biomass increment is needed. Here is an example: carbon dioxide sequestration = (BIT x 0.47) x 3.67; where BIT is biomass increment, 0.47 is carbon conversion factor (Eggleston et al. 2014), and 3.67 is carbon dioxide conversion factor (Meepol 2010). Or, the oxygen production is estimated by this equation: oxygen production = BIT x 1.2; where BIT is biomass increment, 1.2 is the oxygen conversion factor (Yolasiğmaz and Keleş, 2009). The biomass is calculated using DBH and TH, for example:

$W_t = 0.0046\ (DBH^2 \times TH)^{1.2046}$ for *H. brasiliensis* (Trephattanasuwan et al. 2008);

$W_t = 0.0241(DBH^2 \times TH)^{1.0842}$ for *H. odorata* (Viriyabuncha et al. 2004); and $0.0435\ (DBH^2 \times TH)^{0.9370}$ for *A. excelsa* (Viriyabuncha et al. 2004);

$W_s = 0.0509\ (DBH^2 \times TH)^{0.919}$; $W_b = 0.00893\ (DBH^2 \times TH)^{0.977}$; $W_l = 0.0140\ (DBH^2 \times TH)^{0.669}$; and $W_t = W_s + W_b + W_l$ for *S. roxburghii*, *S. macrophylla, D. alatus and A. excelsa* (Tsutsumi et al. 1983);

Where: DBH is the diameter at breast height, TH is total height, W_s is stem biomass, W_b is branch biomass, W_l is leaf biomass, and W_t is above-ground biomass.

The calculation of tree volume also requires DBH and MH parameters. For example, V = 0.42× BA × MH; where V is timber volume, 0.42 is the coefficients of a tree stem's shape, BA is a tree's basal area at breast height (using DBH to calculate) and MH is a tree's merchantable height (Magnussen 2004).

The prediction models from this study are thus useful in such calculations. For example, we can calculate the benefits of carbon sequestration, oxygen production or timber volume of *S. macrophylla* at the age of 20 by using the predicting results in Tables 6 and 7 to estimate the growth size before calculating the relevant amount of ecosystem services. The economic value of these services can then be estimated once the price of the services is multiplied. Table 8 shows an example of applying the results of the prediction models to estimate the carbon dioxide sequestration, oxygen production and timber values of each species at the age of 10 and 20 years.

Discussion

This current study generated 21 models of the relationships between DBH, TH, and MH of six species. Although the current study is based on a small sample of participants, its findings can fill the research gap for now. In the future, when farmers grow more trees or when the data avails, the sample size of economic tree species should be increased. Although the sample size was small, the data varied over a wide range, attributable to the different managements in each plantation such as fertilization pattern and thinning. For example, different thinning patterns may affect the variability of MH of *H. brasiliensis*. Although thinning can increase tree size initially, after rubber tapping, the branches are too high for farmers to trim, thus allowing the tree to branch freely and reducing its size (Fernández et al. 2017). Therefore, similar heights cannot be expected in each plantation, and a wide range of MH thus inevitable. Because of this variability of MH data, the model of rubber trees after tapping results in the models' goodness-of-fit measures highest in terms of error. Another possible explanation for this is that the number and the age distribution of *H. brasiliensis* were much higher and broader than that of the economic forest tree species. This is because planting economic forest trees with rubber is still generally rare in Thailand. At present, from the researchers' interviews with farmers, *H. odorata*, *S. roxburghii* and *S. macrophylla* are the most popular trees because of their high economic values and suitability to grow under the canopy of *H. brasiliensis.* It is thus reflected in the lower number of plants grown in the plantations and made the total number of each economic tree species lower than that of the *H. brasiliensis*.

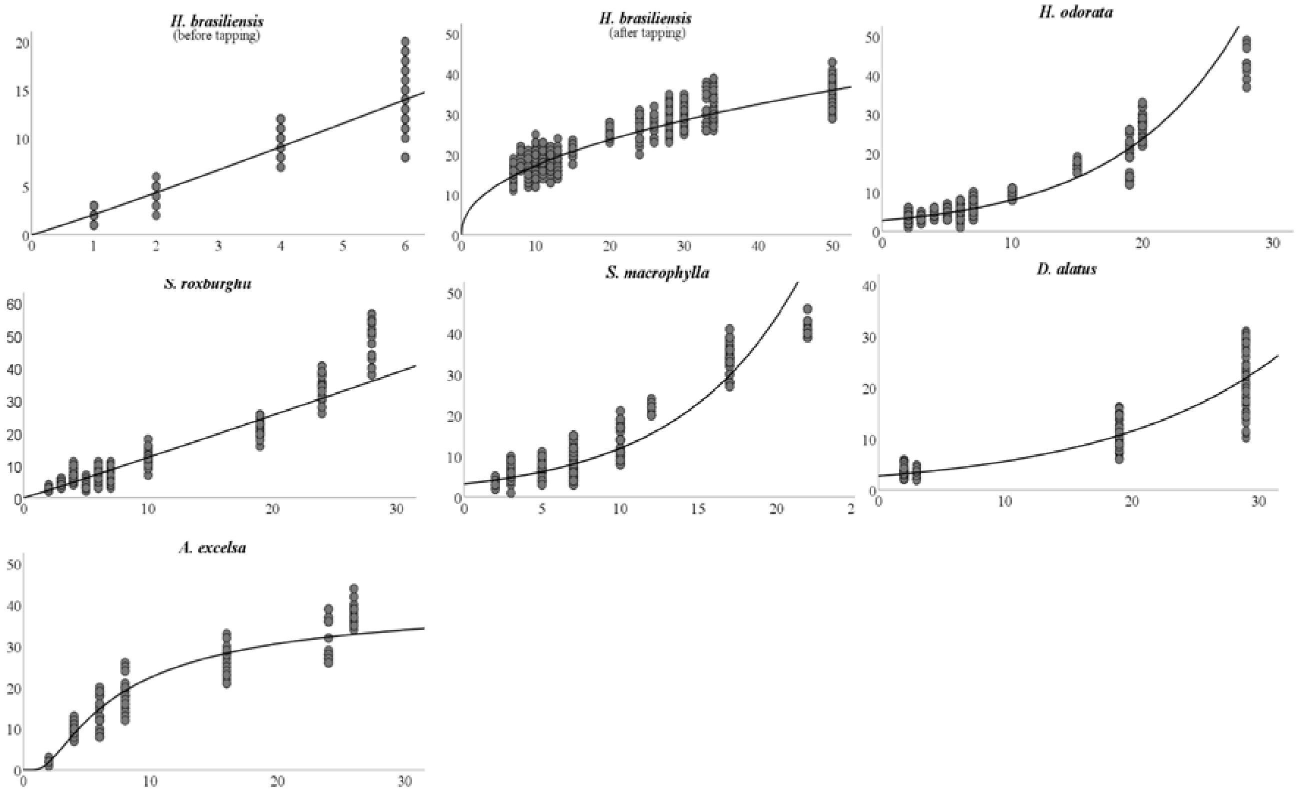

Figure 2. Relationship between DBH and age of trees

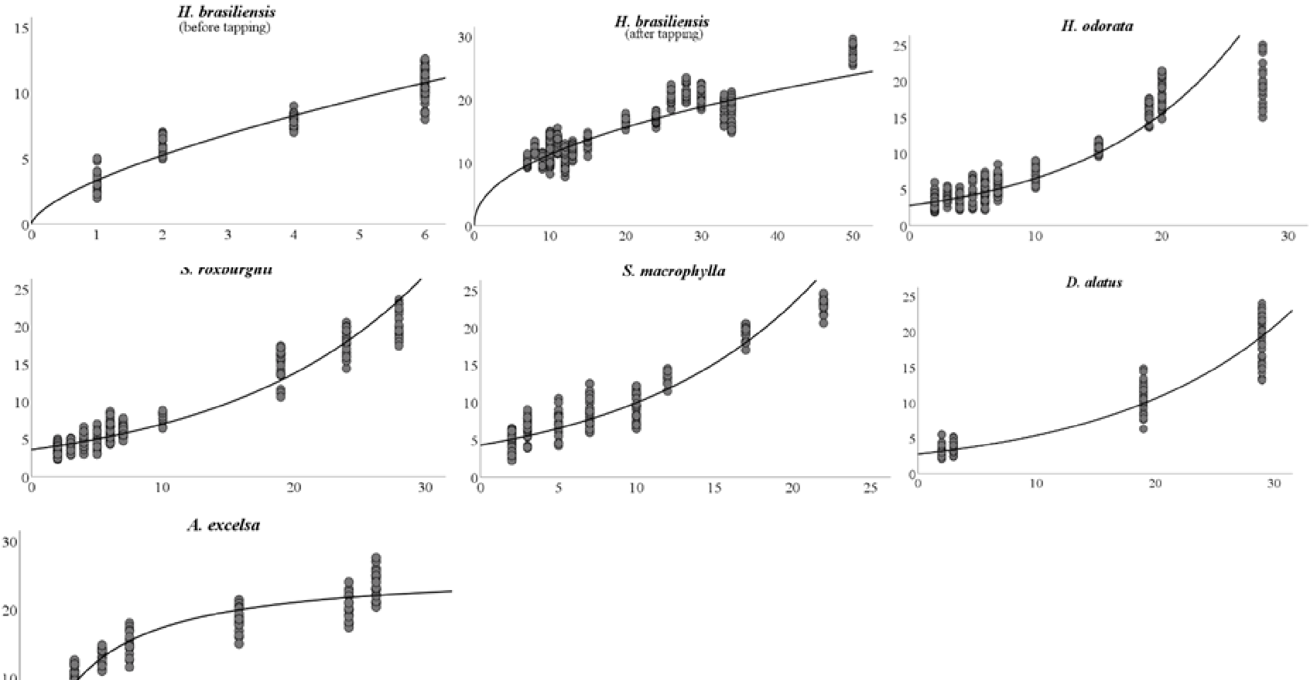

Figure 3. Relationship between TH and age of trees

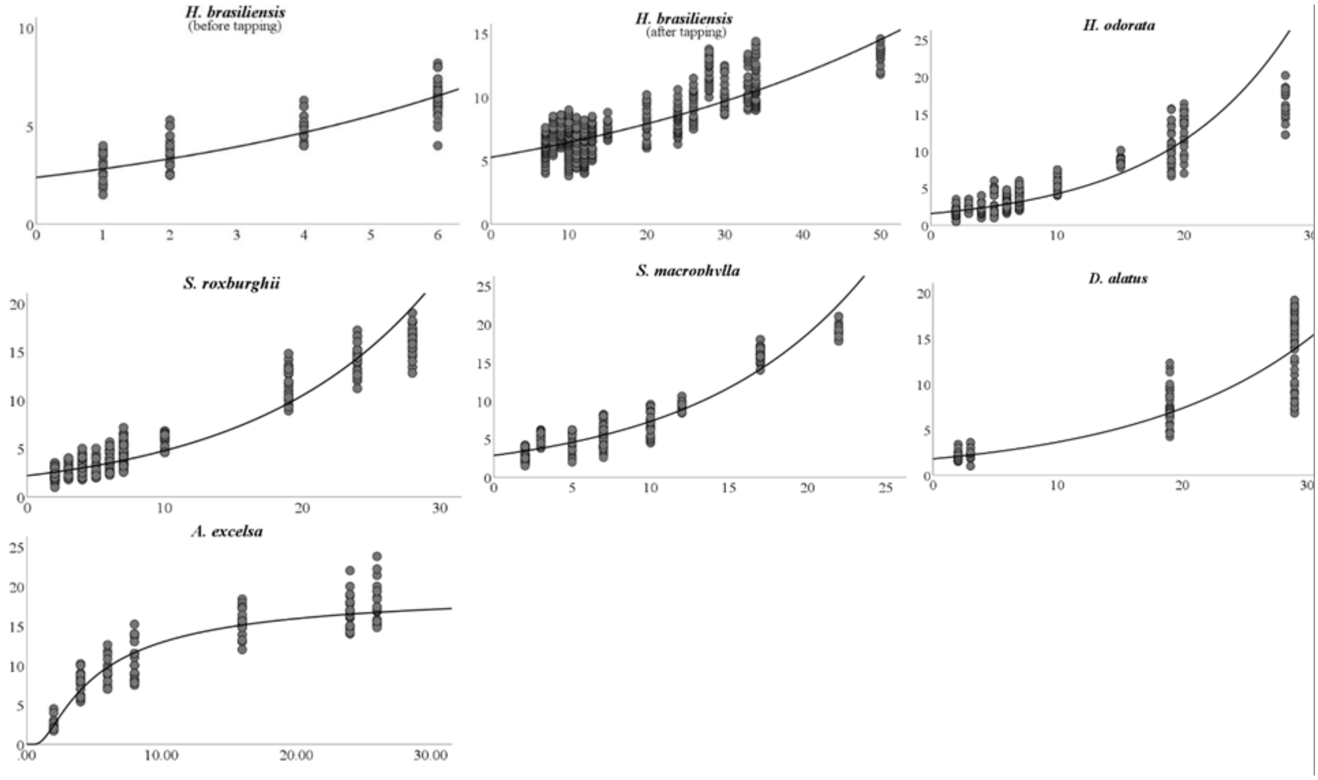

Figure 4. Relationship between MH and age of trees

Table 7 shows the differences in growth patterns which can be explained by the different characteristics of each species, the management of the plantations (Forestry Research Center 2009), genetic variation, and environmental conditions (Roo et al. 2014). The results showed that the growth rate of intercropping was high even though the density of *H. brasiliensis* in this research was as high as 475 trees ha^{-1}. The density was recommended by the Rubber Authority of Thailand (2018) and was a common practice in Thailand, whereas, in some countries, the density was only at 400 trees ha^{-1} (Priyadarshan 2011). Despite that, the growth rate was still high, probably because of the differences in the depth of the root systems of *H. brasiliensis* and the intercropping. Usually, *H. brasiliensis* has the root system in the soil at a depth not exceeding 0.45 meters (Chugamnerd 1998; George et al. 2009), whereas the intercropping trees have a deep root system (Charernjiratragul et al. 2015) at one meter (Maeght 2013). Therefore, the nutrient competition between *H. brasiliensis* and the intercropping is low. In addition, the soil in rubber plantations with intercropping is more fertile than that in monoculture systems (Bumrungsri et al. 2011). This is due to high litterfall from a variety of species and more nutrients added to the soil because of a high number of trees (Wibawa et al. 2007; Bumrungsriet al. 2011). The complexity of the canopy and the root system in the plantation can reduce soil erosion (Witthawatchutikul 1993; Wibawa et al. 2007; Kittitornkool et al. 2014) which therefore can preserve the nutrients necessary for the growth of trees. Furthermore, the high canopy cover helps maintain air temperature (Yunis et al. 1990; Brooks and Kyker-Snowman. 2008) and soil moisture (Islam et al. 2016; Özkan and Gökbulak, 2017) in which the accelerated rate of litter decomposition becomes soil nutrients (Golley 1983; Swift and Anderson 1989).

To test the accuracy of the models, we compared the predicted results of the models to the observed data available in the presently scarce literature. Due to the limited data availability, uniformed comparisons for each species and each growth parameter were not possible. Whereas the verification of five out of six species can be done with the DBH, it was not possible with the TH, possibly because measuring tree height is difficult, and usually entails much error (Luoma et al. 2017). The predicted DBH of *H. brasiliensis, S. macrophylla* and *A. excelsa* were compared to the data from the Rubber Research Institute's experimental monoculture plots in the southern region, whereas *H. odorata*, and *D. alatus* were compared to the data from the experimental plots in the northeastern region. The predicted TH of *S. macrophylla, H. odorata*, and *D. alatus* were also compared to the data from the experimental plots outside the southern region.

Table 1. Summary of the site characteristics

Province	Average annual precipitation (mm) and temperature (°C)	Species	Age	Number of sites	Number of tree	DBH (cm)				TH (m)				MH (m)			
						Min	Max	Mean	S.D.	Min	Max	Mean	S.D	Min	Max	Mean	S.D.
Songkhla	1,600-2,000	*H. brasiliensis*	6-34	30	510	7.9	37.9	19.6	5.5	7.8	22.4	13.0	3.4	3.0	14.0	7.1	1.9
	26-28	*H. odorata*	2-28	16	434	1.0	48.6	8.6	9.0	1.9	25.0	6.4	4.6	0.5	20.2	4.4	3.9
		S. roxburghii	2-28	10	278	1.6	56.5	14.2	15.4	2.3	23.5	8.5	6.2	1.0	19.0	6.3	5.3
		S. macrophylla	2-22	8	183	1.3	45.9	15.1	13.3	2.2	24.6	10.4	6.5	1.5	21.0	8.1	5.6
		D. alatus	2-29	6	144	2.0	31.0	11.6	10.1	2.1	24.0	10.0	7.8	1.0	19.2	7.3	6.2
		A. excelsa	2-26	6	111	1.0	44.4	21.7	12.8	2.1	27.6	15.6	6.8	1.7	23.8	12.1	5.7
Phattalung	2,000-2,400	*H. brasiliensis*	1-50	10	300	1.0	43.3	17.9	10.8	2.0	29.6	13.2	7.3	1.5	14.6	7.6	3.5
	26-28	*H. odorata*	7-20	3	87	3.0	3.3	13.1	9.8	3.4	21.4	9.5	6.5	2.0	16.4	6.5	4.6
		S. roxburghii	6-7	3	90	3.0	11.4	6.9	1.9	4.3	8.7	6.3	0.9	2.3	7.2	4.3	1.1
		S. macrophylla	7	2	60	3.0	15.3	8.4	3.5	6.0	12.5	8.4	1.8	2.6	8.2	5.4	1.5
		A. excelsa	6	1	20	7.8	19.8	14.2	3.8	11.0	14.8	13.0	1.2	7.0	12.6	9.1	1.6
Trang	2,000-2,400	*H. brasiliensis*	24-34	2	60	24.0	34.0	29.0	5.0	20.2	35.0	28.5	2.6	6.3	10.6	8.7	0.9
	26-28	*D. alatus*	19	1	30	6.0	16.2	11.3	3.1	6.3	14.8	11.0	2.0	4.2	12.3	7.6	2.0

Table 2. Number of trees studied

Tree	Number of studied trees (number of plantations)					
	1-10 year	**11-20 year**	**21-30 year**	**31-40 year**	**41-50 year**	**Total**
H. brasiliensis	371 (13)	240 (9)	120 (4)	104 (4)	30 (1)	865
H. odorata	413 (16)	88 (4)	20 (1)	-	-	521
S. roxburghii	290 (11)	25 (1)	53 (2)	-	-	368
S. macrophylla	188 (10)	40 (2)	15 (1)	-	-	243
D. alatus	96 (5)	41 (2)	57 (3)	-	-	194
A. excelsa	73 (4)	19 (1)	39 (2)	-	-	131

Note: The age of trees were from the farmers who kept track of the planting year

Table 3. Descriptive analysis results of the data set

Tree	Descriptive statistics							
	N	**Growth variable**	**Min**	**Max**	**Mean**	**S.D.**	**Skewness**	**Kurtosis**
H. brasiliensis before tapping	140	DBH	1.00	20.00	8.8667	5.25161	.228	-.989
		TH	2.00	12.60	7.7353	3.01765	-.258	-1.052
		MH	1.50	8.20	4.8300	1.66998	-.117	-1.065
H. brasiliensis after tapping	725	DBH	8.00	43.00	21.8458	6.59708	.590	-.348
		TH	7.80	29.60	14.4688	4.63903	1.040	.600
		MH	3.80	14.60	7.9338	2.36314	.817	.101
H. odorata	521	DBH	1.00	49.00	9.3205	9.31722	2.219	4.653
		TH	1.90	25.00	6.9555	5.12045	1.586	1.515
		MH	0.50	20.20	4.7560	4.07007	1.692	2.149
S. roxburghii	368	DBH	2.00	56.53	12.4330	13.81831	1.840	2.280
		TH	2.30	23.50	7.9568	5.48044	1.376	.516
		MH	1.00	19.00	5.8021	4.68275	1.371	.479
S. macrophylla	243	DBH	1.00	46.00	13.3868	12.00648	1.264	.272
		TH	2.20	24.60	9.8782	5.73561	1.082	.074
		MH	1.50	21.00	7.4374	5.04834	1.249	.301
D. alatus	174	DBH	1.97	31.00	11.5709	9.27484	.755	-.793
		TH	2.10	24.00	10.2144	7.14712	.433	-1.249
		MH	1.00	19.20	7.3227	5.70456	.714	-.846
A. excelsa	131	DBH	1.00	44.00	20.5496	12.17514	.092	-1.148
		TH	2.10	27.60	15.2374	6.35854	-.389	-.434
		MH	1.70	23.80	11.6622	5.41815	-.117	-.871

Table 9 shows different approximation between the predicted and the observed DBH and TH. The results of the DBH and TH prediction for *H. brasiliensis, S. macrophylla, and D. alatus* appear to be lower than the available studies. One possible explanation is that the data from other studies were from the controlled monoculture experimental plots, whereas the data in this study came from a variety of actual intercropping plantations which differ in micro-environmental conditions. In controlled experimental plots, the environment where trees were grown was similar; therefore, trees generally produced similar sizes in a similar age range. In contrast, the actual plantations were growing in different environmental conditions; thus, trees were different in size and age. Another vital explanation of the lower growth rate from the prediction models is the tapping systems. In this study, the farmers applied the higher-frequency tapping system (3-days tapping followed by 1-day rest), while the controlled plots applied the alternate daily tapping. The high frequency of the tapping system may slow the *H. brasiliensis* growth rate down (Rubber Research Institute of Thailand 2018). The predicted DBHs of *A. excelsa* were higher than one study but lower than another study, whereas the TH was slightly higher than the only study found. Note that the prediction of *S. macrophylla* in the study area suggested a higher growth rate at the older ages than in the literature, which may be related to precipitation. For example, Shono and Snook (2006) found that the growth rate of *S. macrophylla* increased according to the annual precipitation. In this study area, the annual precipitation (1,600-2,400 mm) is higher than some other studies: southeast Para´state, Brazil 1,859 mm (Grogan et al. 2010), Quintana Roo, Mexico 1300 mm (Roo et al. 2014), and northwestern Belize, Mexico 1600 mm (Shono and Snook 2006). This may contribute to the reason that *S. macrophylla* growth rates in this study were high.

To our knowledge, there is no available model to predict MH in Thailand for these species that were included in this study. Unlike other ecosystem services, MH is the parameter that the farmers are most interested in because it is more tangible than carbon storage or oxygen production. Thus it is significant for them to be able to predict the MH and calculate this provisioning service. The contribution of this study is a tool that enables the farmers and relevant stakeholders to calculate this particular benefit of intercropping.

In conclusion, the tree growth prediction models of five species were generated, which can be used to predict the DBH, TH, and MH at any particular age. The contribution of these models provides a powerful tool for valuing ecosystem services from these trees at various ages more accurately, particularly those ecological service values that need a tree size in the calculation - primarily carbon sequestration, oxygen production, and wood production. Researchers, farmers, and policymakers can directly use the models to predict DBH, TH, and MH which would benefit future planning or promoting the intercropping in a rubber plantation to secure maximum benefit both financially and environmentally. The growth prediction of trees at any age can also benefit the project related to payment for ecosystem service too. However, due to the small-size sample of the economic trees, the application of the models to be used elsewhere must consider the tree species and the climatic conditions that are similar to our study area. Future research should include older trees and other tree species intercropped in the rubber plantation, which are constrained in this study. This is to promote environmentally friendly farming practices that serve for improving ecological benefits and contributing to the global effect.

Table 4. The models predicting tree growth parameters (DBH, TH, MH)

Tree species	Regression type	Regression model
H. brasiliensis	Power	$\mathrm{DBH} = 2.095x^{1.060}$
(before tapping)	Power	$\mathrm{TH} = 3.337x^{0.655}$
	Exponential	$\mathrm{MH} = 2.387e^{0.167x}$
H. brasiliensis	Power	$\mathrm{DBH} = 5.845x^{0.467}$
(after tapping)	Power	$\mathrm{TH} = 3.850x^{0.468}$
	Exponential	$\mathrm{MH} = 5.276e^{0.020x}$
H. odorata	Exponential	$\mathrm{DBH} = 2.748e^{0.108x}$
	Exponential	$\mathrm{TH} = 2.777e^{0.086x}$
	Exponential	$\mathrm{MH} = 1.575e^{0.099x}$
S. roxburghii	Power	$\mathrm{DBH} = 1.160x^{1.030}$
	Exponential	$\mathrm{TH} = 3.580e^{0.067x}$
	Exponential	$\mathrm{MH} = 2.190e^{0.078x}$
S. macrophylla	Exponential	$\mathrm{DBH} = 3.248e^{0.130x}$
	Exponential	$\mathrm{TH} = 4.281e^{0.084x}$
	Exponential	$\mathrm{MH} = 2.859e^{0.094x}$
D. alatus	Exponential	$\mathrm{DBH} = 2.746e^{0.072x}$
	Exponential	$\mathrm{TH} = 2.752e^{0.067x}$
	Exponential	$\mathrm{MH} = 1.801e^{0.070x}$
A. excelsa	Sigmoid	$\mathrm{DBH} = e^{3.733-6.227/x}$
	Sigmoid	$\mathrm{TH} = e^{3.253-4.147/x}$
	Sigmoid	$\mathrm{MH} = e^{2.978-4.204/x}$

DBH; diameter at breast height, TH; total height, MH; merchantable height and x; age of tree (year)

Table 5. Key goodness-of-fit measures for regression analysis of the models

Tree species	Type	Adjusted R^2	Std error of the estimate	SST (Total sum of squares)	Mean squared residual	Model Sig.	p value	
							constant	b1
H. brasiliensi	DBH							
before tapping	Linear	.826	2.193	4109.333	4.811	.000	1.000	.000
	Logarithm	.808	2.303	4109.333	5.306	.000	.001	.000
	Power	.909	.233	89.258	.054	.000	.000	.000
	S	.889	.258	89.258	.066	.000	.000	.000
	Growth	.839	.310	89.258	.096	.000	.000	.000
	Exponential	.839	.310	89.258	.096	.000	.000	.000
	TH							
	Linear	.898	.963	1356.823	.927	.000	.000	.000
	Logarithm	.901	.952	1356.823	.906	.000	.000	.000
	Power	.893	.158	34.684	.025	.000	.000	.000
	S	.892	.159	34.684	.025	.000	.000	.000
	Growth	.821	.204	34.684	.042	.000	.000	.000
	Exponential	.821	.204	34.684	.042	.000	.000	.000
	MH							
	Linear	.792	.761	415.535	.579	.000	.000	.000
	Logarithm	.755	.827	415.535	.684	.000	.000	.000
	Power	.755	.195	23.054	.038	.000	.000	.000
	S	.684	.221	23.054	.049	.000	.000	.000
	Growth	.754	.195	23.054	.038	.000	.000	.000
	Exponential	.754	.195	23.054	.038	.000	.000	.000

H. brasiliensi after tapping	DBH							
	Linear	.794	2.993	31291.888	8.957	.000	.000	.000
	Logarithm	.808	2.888	31291.888	8.338	.000	.000	.000
	Power	.776	.142	64.858	.020	.000	.000	.000
	S	.734	.155	64.858	.024	.000	.000	.000
	Growth	.725	.157	64.858	.025	.000	.000	.000
	Exponential	.725	.157	64.858	.025	.000	.000	.000
	TH							
	Linear	.826	1.935	15473.282	3.746	.000	.000	.000
	Logarithm	.786	2.145	15473.282	4.602	.000	.000	.000
	Power	.793	.135	63.863	.018	.000	.000	.000
	S	.709	.161	63.863	.026	.000	.000	.000
	Growth	.787	.138	63.863	.019	.000	.000	.000
	Exponential	.787	.138	63.863	.019	.000	.000	.000
	MH							
	Linear	.679	1.338	4015.210	1.791	.000	.000	.000
	Logarithm	.618	1.461	4015.210	2.136	.000	.000	.000
	Power	.576	.187	59.497	.035	.000	.000	.000
	S	.468	.210	59.497	.044	.000	.000	.000
	Growth	.615	.179	59.497	.032	.000	.000	.000
	Exponential	.615	.179	59.497	.032	.000	.000	.000
H. odorata	DBH							
	Linear	.904	2.887	45141.470	8.332	.000	.000	.000
	Logarithm	.660	5.434	45141.470	29.530	.000	.000	.000
	Power	.811	.332	302.319	.110	.000	.000	.000
	S	.557	.507	302.319	.257	.000	.000	.000
	Growth	.859	.286	302.319	.082	.000	.000	.000
	Exponential	.859	.286	302.319	.082	.000	.000	.000
	TH							
	Linear	.903	1.597	13633.887	2.549	.000	.000	.000
	Logarithm	.730	2.660	13633.887	7.073	.000	.000	.000
	Power	.804	.274	199.412	.075	.000	.000	.000
	S	.562	.410	199.412	.168	.000	.000	.000
	Growth	.828	.256	199.412	.066	.000	.000	.000
	Exponential	.828	.256	199.412	.066	.000	.000	.000
	MH							
	Linear	.894	1.328	8614.043	1.763	.000	.429	.000
	Logarithm	.712	2.185	8614.043	4.775	.000	.000	.000
	Power	.779	.344	278.524	.118	.000	.000	.000
	S	.550	.491	278.524	.241	.000	.000	.000
	Growth	.792	.334	278.524	.111	.000	.000	.000
	Exponential	.792	.334	278.524	.111	.000	.000	.000
S. roxburghii	DBH							
	Linear	.919	3.935	70077.039	15.482	.000	.000	.000
	Logarithm	.728	7.205	70077.039	51.973	.000	.000	.000
	Power	.857	.341	298.750	.116	.000	.000	.000
	S	.652	.532	298.750	.283	.000	.000	.000
	Growth	.856	.342	298.750	.117	.000	.000	.000
	Exponential	.856	.342	298.750	.117	.000	.000	.000
	TH							
	Linear	.953	1.185	11022.907	1.405	.000	.000	.000
	Logarithm	.823	2.303	11022.907	5.303	.000	.000	.000
	Power	.878	.204	124.757	.042	.000	.000	.000
	S	.625	.357	124.757	.128	.000	.000	.000
	Growth	.887	.196	124.757	.038	.000	.000	.000
	Exponential	.887	.196	124.757	.038	.000	.000	.000
	MH							
	Linear	.945	1.100	8047.621	1.209	.000	.000	.000
	Logarithm	.805	2.070	8047.621	4.238	.000	.000	.000
	Power	.838	.279	176.027	.078	.000	.000	.000
	S	.583	.447	176.027	.200	.000	.000	.000
	Growth	.853	.266	176.027	.071	.000	.000	.000
	Exponential	.853	.266	176.027	.071	.000	.000	.000

S. macrophylla	DBH							
	Linear	.899	3.808	34885.638	14.497	.000	.000	.000
	Logarithm	.692	6.661	34885.638	44.365	.000	.000	.000
	Power	.772	.406	175.004	.165	.000	.000	.000
	S	.604	.535	175.004	.286	.000	.000	.000
	Growth	.816	.364	175.004	.133	.000	.000	.000
	Exponential	.816	.364	175.004	.133	.000	.000	.000
	TH							
	Linear	.897	1.842	7961.114	3.393	.000	.000	.000
	Logarithm	.730	2.981	7961.114	8.888	.000	.003	.000
	Power	.776	.264	75.285	.070	.000	.000	.000
	S	.638	.336	75.285	.113	.000	.000	.000
	Growth	.796	.252	75.285	.063	.000	.000	.000
	Exponential	.796	.252	75.285	.063	.000	.000	.000
	MH							
	Linear	.883	1.728	6167.549	2.985	.000	.000	.000
	Logarithm	.676	2.872	6167.549	8.249	.000	.000	.000
	Power	.729	.322	92.493	.104	.000	.000	.000
	S	.562	.409	92.493	.167	.000	.000	.000
	Growth	.802	.275	92.493	.076	.000	.000	.000
	Exponential	.802	.275	92.493	.076	.000	.000	.000
D. alatus	DBH							
	Linear	.791	4.237	14881.911	17.949	.000	.052	.000
	Logarithm	.688	5.177	14881.911	26.802	.000	.002	.000
	Power	.848	.346	136.280	.120	.000	.000	.000
	S	.746	.448	136.280	.200	.000	.000	.000
	Growth	.898	.283	136.280	.080	.000	.000	.000
	Exponential	.898	.283	136.280	.080	.000	.000	.000
	TH							
	Linear	.895	2.321	8837.074	5.387	.000	.000	.000
	Logarithm	.813	3.090	8837.074	9.548	.000	.001	.000
	Power	.920	.231	116.136	.053	.000	.000	.000
	S	.855	.312	116.136	.097	.000	.000	.000
	Growth	.933	.212	116.136	.045	.000	.000	.000
	Exponential	.933	.212	116.136	.045	.000	.000	.000
	MH							
	Linear	.793	2.595	5629.773	6.733	.000	.010	.000
	Logarithm	.711	3.066	5629.773	9.398	.000	.002	.000
	Power	.882	.299	130.943	.089	.000	.000	.000
	S	.811	.378	130.943	.143	.000	.000	.000
	Growth	.901	.273	130.943	.075	.000	.000	.000
	Exponential	.901	.273	130.943	.075	.000	.000	.000
A. excelsa	DBH							
	Linear	.867	4.434	19270.427	19.657	.000	.000	.000
	Logarithm	.903	3.789	19270.427	14.355	.000	.000	.000
	Power	.833	.382	113.893	.146	.000	.000	.000
	S	.944	.221	113.893	.049	.000	.000	.000
	Growth	.616	.580	113.893	.337	.000	.000	.000
	Exponential	.616	.580	113.893	.337	.000	.000	.000
	TH							
	Linear	.786	2.941	5256.027	8.651	.000	.000	.000
	Logarithm	.906	1.946	5256.027	3.785	.000	.929	.000
	Power	.774	.297	50.830	.088	.000	.000	.000
	S	.939	.155	50.830	.024	.000	.000	.000
	Growth	.544	.422	50.830	.178	.000	.000	.000
	Exponential	.544	.422	50.830	.178	.000	.000	.000
	MH							
	Linear	.781	2.535	3816.325	6.426	.000	.000	.000
	Logarithm	.872	1.938	3816.325	3.757	.000	.025	.000
	Power	.812	.279	53.840	.078	.000	.000	.000
	S	.910	.193	53.840	.037	.000	.000	.000
	Growth	.605	.405	53.840	.164	.000	.000	.000
	Exponential	.605	.405	53.840	.164	.000	.000	.000

Table 6. Predicted growth size with 95% prediction intervals

Age (year)	***H. brasiliensis***			***H. odorata***			***S. roxburghii***			***S. macrophylla***			***D. alatus***			***A. Excelsa***		
	DBH	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**
1	2.10 (1.31-3.34)	3.34 (2.43-4.57)	2.82 (1.91-4.16)	3.06 (1.74-5.38	3.03 (1.83-5.01)	1.74 (.90-3.36)	1.16 (.59-2.28)	3.83 (2.60-5.64)	2.37 (1.40-3.40)	3.70 (1.80-7.61)	4.66 (2.83-7.67)	3.14 (1.82-5.41)	2.95 (1.68-5.17)	2.94 (1.93-4.48)	1.93 (1.22-3.33)	0.08 (0.05-0.13	0.41 (0.29-0.58)	0.29 (0.19-0.45)
2	4.37 (2.75-6.94)	5.25 (3.84-7.19)	3.33 (2.26-4.92)	3.41 (1.94-5.99)	3.30 (1.99-5.46)	1.92 (1.00-3.71)	2.37 (1.21-4.64)	4.09 (2.78-6.03)	2.56 (1.52-4.32)	4.21 (2.05-8.67)	5.06 (3.08-8.34)	3.45 (2.00-5.94)	3.17 (1.81-5.56)	3.15 (2.07-4.79)	2.07 (1.21-3.57)	1.86 (1.19-2.90)	3.25 (2.37-4.45)	2.40 (1.62-3.55)
3	6.71 (4.23-10.65)	6.85 (5.01-9.37)	3.94 (2.68-5.80)	3.80 (2.16-6.67)	3.59 (2.17-5.95)	2.12 (1.10-4.10)	3.60 (1.83-7.04)	4.38 (2.97-6.44)	2.77 (1.64-4.67)	4.80 (2.34-9.87)	5.51 (3.35-9.07)	3.79 (2.20-6.52)	3.41 (1.94-5.97)	3.36 (2.21-5.13)	2.22 (1.29-3.82)	5.25 (3.37-8.15)	6.49 (4.77-8.85)	4.84 (3.29-7.11)
4	9.11 (5.74-14.76)	8.27 (6.05-11.31)	4.66 (3.16-6.86)	4.23 (2.41-7.43)	3.92 (2.36-6.48)	2.34 (1.21-4.52)	4.84 (2.47-9.46)	4.68 (3.18-6.89)	2.99 (1.77-5.05)	5.46 2.66-11.24)	5.99 (3.65-9.87)	4.16 (2.42-7.17)	3.66 (2.09-6.40)	3.60 (2.37-5.48)	2.38 (1.39-4.10)	8.81 (5.68-13.68)	9.17 (6.74-12.48)	6.87 (4.68-10.08)
5	11.54 (7.26-18.32)	9.58 (7.00-13.10)	5.50 (3.74-8.11)	4.72 (2.68-8.27)	4.27 (2.58-7.07)	2.58 (1.34-4.99)	6.09 (3.11-11.90)	5.00 (3.40-7.37)	3.23 (1.92-5.46)	6.22 3.03-12.80)	6.52 (3.97-10.73)	4.57 (2.66-7.87)	3.94 (2.24-6.88)	3.85 (2.53-5.86)	2.56 (1.49-4.40)	12.03 (7.75-18.66)	11.29 (8.30-15.36)	8.48 (5.78-12.43)
6	14.00 (8.81-22.24)	10.79 (7.88-14.76)	6.50 (4.41-9.59)	5.25 (2.99-9.21)	4.65 (2.81-7.70)	2.85 (1.48-5.51)	7.34 (3.75-14.36)	5.35 (3.64-7.88)	3.50 (2.08-5.91)	7.09 (3.46-14.58)	7.09 (4.32-11.68)	5.03 (2.92-8.64)	4.23 (2.41-7.39)	4.11 (2.71-6.27)	2.74 (1.60-4.72)	14.81 (9.54-22.97)	12.96 (9.53-17.63)	9.75 (6.645-14.30)
7	14.50 (10.95-19.14)	9.57 (7.33-12.48)	6.07 (4.28-8.63)	5.85 (3.33-10.26	5.07 (3.06-8.39)	3.15 (1.64-6.09)	8.61 (4.39-16.83)	5.72 (3.89-8.43)	3.78 (2.24-6.39)	8.07 (3.94-16.60)	7.71 (4.70-12.70)	5.52 (3.21-9.49)	4.55 (2.59-7.93)	4.40 (2.90-6.70)	2.94 (1.71-5.06)	17.17 (11.07-26.64)	14.30 (10.52-19.46)	10.78 (7.35-15.81)
8	15.44 (11.64-20.37)	10.19 (7.80-13.28)	6.19 (4.36-8.80)	6.52 (3.71-11.43)	5.53 (3.34-9.15)	3.48 (1.81-6.73)	9.88 (5.04-19.31)	6.12 (4.16-9.01)	4.09 (2.43-6.91)	9.19 (4.49-18.91)	8.38 (5.12-13.82)	6.06 (3.52-10.43)	4.88 (2.78-8.52)	4.70 (3.10-7.17)	3.15 (1.84-5.43)	19.19 (12.37-29.77)	15.40 (11.33-20.96)	11.62 (7.92-17.04)
9	16.31 (12.31-21.52)	10.77 (8.24-14.03)	6.32 (4.45-8.98)	7.26 (4.13-12.73)	6.02 (3.63-9.97)	3.84 (2.00-7.42)	11.15 (5.69-21.80)	6.54 (4.45-9.64)	4.42 (2.62-7.47)	10.47 (5.11-21.55)	9.12 (5.57-15.04)	6.66 (3.87-11.45)	5.25 (2.98-9.156)	5.03 (3.32-7.67)	3.38 (1.97-5.82)	20.93 (13.49-32.47)	16.32 (12.00-22.20	12.32 (8.39-18.07)
10	17.13 (12.93-22.60)	11.31 (8.66-14.74)	6.44 (4.54-9.16)	8.09 (4.60-14.18)	6.56 (3.96-10.86)	4.24 (2.20-8.19)	12.43 (6.34-24.31)	7.00 (4.76-10.31)	4.78 (2.84-8.08)	11.92 5.82-24.55)	9.92 (6.06-16.37)	7.32 (4.25-12.58)	5.64 (3.21-9.83)	5.38 (3.55-8.20)	3.63 (2.12-6.25)	22.43 (14.45-34.80)	17.09 (12.56-23.25)	12.90 (8.79-18.93)
11	17.91 (13.51-23.62)	11.83 (9.05-15.41)	6.57 (4.63-9.35)	9.01 (5.12-15.79)	7.15 (4.32-11.84)	4.68 (2.43-9.05)	13.71 (6.99-26.82)	7.48 (5.09-11.02)	5.16 (3.07-8.74)	13.57 (6.63-27.97)	10.79 (6.59-17.81)	8.04 (4.67-13.83)	6.06 (3.45-10.56)	5.75 (3.80-8.77)	3.89 (2.27-6.70)	23.73 (15.29-36.83)	17.74 (13.04-24.15)	13.41 (9.14-19.67)
12	18.65 (14.07-24.60)	12.32 (9.43-16.05)	6.71 (4.73-9.54)	10.04 (5.70-17.59)	7.79 (4.70-12.90)	5.17 (2.69-10.00)	15.00 (7.64-29.33)	8.00 (5.44-11.79)	5.58 (3.32-9.45)	15.46 (7.55-31.87)	11.73 (7.17-19.38)	8.83 (5.13-15.19)	6.52 (3.70-11.34)	6.15 (4.06-9.38)	4.17 (2.44-7.18)	24.88 (16.03-38.61)	18.31 (13.46-24.92)	13.84 (9.43-20.31)
13	19.36 (14.61-25.54)	12.79 (9.79-16.66)	6.84 (4.82-9.73)	11.19 (6.35-19.59)	8.49 (5.12-14.06)	5.70 (2.97-11.05)	16.29 (8.30-31.86)	8.55 (5.82-12.61)	6.04 (3.59-10.22)	17.60 (8.60-36.32)	12.76 (7.80-21.10)	9.70 (5.63-16.69)	7.00 (3.98-12.19)	6.58 (4.34-10.04)	4.47 (2.62-7.71)	25.89 (16.68-40.18)	18.80 (13.82-25.59)	14.22 (9.69-20.87)
14	20.05 (15.12-26.43)	13.24 (10.13-17.25)	6.98 (4.92-9.93)	12.46 (7.07-21.82)	9.26 (5.58-15.32)	6.30 (3.28-12.20)	17.58 (8.96-34.39)	9.15 (6.23-13.49)	6.53 (3.88-11.05)	20.05 (9.79-41.40)	13.88 (8.49-22.96)	10.66 (6.18-18.34)	7.52 (4.27-13.09)	7.03 (4.65-10.74)	4.80 (2.80-8.27)	26.79 (17.26-41.58)	19.24 (14.14-26.18)	14.55 (9.91-21.36)
15	20.70 (15.62-27.30)	13.67 (10.46-17.82)	7.12 (5.02-10.13)	13.89 (7.87-20.31)	10.09 (6.08-16.70)	6.95 (3.62-13.48)	18.87 (9.62-36.93)	9.78 (6.66-14.42)	7.06 (4.19-11.95)	22.83 (11.15-41.18)	15.09 (9.23-25.00)	11.71 (6.79-20.15)	8.09 (4.59-14.06)	7.52 (4.97-11.48)	5.15 (3.01-8.87)	27.60 (17.78-42.84)	19.62 (14.42-26.71)	14.85 (10.11-21.79)
16	21.34 (16.09-28.13)	14.09 (10.78-18.36)	7.27 (5.12-10.34)	15.47 (8.77-27.08)	10.99 (6.63-18.20)	7.68 (4.00-14.89)	20.17 (10.28-9.47)	10.46 (7.12-15.43)	7.63 (4.54-12.92)	26.00 (12.69-53.78)	16.41 (10.04-27.21)	12.86 (7.45-22.15)	8.69 (4.93-15.10)	8.04 (5.31-12.28)	5.52 (3.23-9.52)	28.33 (18.24-43.97)	19.96 (14.67-27.17)	15.11 (10.29-22.18)
17	21.95 (16.56-28.93)	14.50 (11.09-18.89)	7.41 (5.23-10.55)	17.23 (9.76-30.16)	11.98 (7.22-19.84)	8.48 (4.41-16.45)	21.47 (10.94-42.02)	11.18 (7.61-16.50)	8.25 (4.90-13.98)	29.61 (14.45-61.31)	17.85 (10.92-29.62)	14.13 (8.18-24.34)	9.34 (5.30-16.23)	8.60 (5.69-13.14)	5.92 (3.46-10.21)	28.98 (18.66-44.99)	20.27 (14.89-27.59)	15.34 (10.45-22.52)
18	22.54 (17.00-29.72)	14.89 (11.39-19.40)	7.56 (5.33-10.76)	19.20 (10.87-33.60)	13.06 (7.87-21.63)	9.36 (4.87-18.17)	22.77 (11.60-44.57)	11.96 (8.14-17.65)	8.92 (5.30-15.12)	33.72 (16.44-69.90)	19.42 (11.87-32.25)	15.53 (8.98-26.76)	10.04 (5.69-17.43)	9.19 (6.08-14.06)	6.35 (3.72-10.96)	29.58 (19.05-45.92)	20.54 (15.10-27-97)	15.56 (10.60-22.84)
19	23.12 (17.44-30.48)	15.27 (11.69-19.90)	7.72 (5.44-10.98)	21.39 (12.10-37.43)	14.23 (8.57-23.57)	10.33 (5.38-20.07)	24.08 (12.26-47.13)	12.79 (8.70-18.88)	9.64 (5.73-16.35)	38.40 (18.71-79.70)	21.12 (12.91-35.11)	17.06 (9.86-29.41)	10.78 (6.11-18.72)	9.83 (6.50-15.34)	6.81 (3.99-11.75)	30.12 (19.40-46.76)	20.80 (15.28-28.31)	15.75 (10.73-23.12)
20	23.68 (17.86-31.21)	15.64 (11.97-20.38)	7.87 (5.55-11.20)	23.83 (13.48-41.71)	15.51 (9.34-25.69)	11.41 (5.94-22.17)	25.38 (12.92-49.70)	13.67 (9.31-20.19)	10.42 (6.20-17.68)	43.73 (21.30-90.88)	22.97 (14.04-38.23)	18.74 (10.82-32.33)	11.59 (6.56-20.12)	10.51 (6.96-16.08)	7.30 (4.28-12.61)	30.62 (19.72-47.54)	21.02 (15.45-28.62)	15.92 (10.84-23.38)
21	24.22 (18.27-31.93)	16.01 (12.24-20.85)	8.03 (5.67-11.43)	26.55 (15.00-46.46)	16.90 (10.18-28.00)	12.59 (6.56-24.50)	26.69 (13.59-52.26)	14.62 (9.95-21.60)	11.27 (6.70-19.13)	49.80 (24.24-103.64)	24.98 (15.26-41.63)	20.58 (11.88-35.54)	12.46 (7.05-21.61)	11.24 (7.44-17.21)	7.83 (4.59-13.53)	31.08 (20.01-48.25)	21.23 (15.60-28.91)	16.08 (10.95-23.61)
22	24.76 (18.67-32.63)	16.36 (12.52-21.31)	8.19 (5.78-11.66)	29.57 (16.71-51.77)	18.42 (11.09-30.53)	13.91 (7.24-27.07)	28.00 (14.25-54.84)	15.63 (10.64-23.10)	12.18 (7.24-20.69)	56.72 (27.58-118.20)	27.17 (16.60-45.33)	22.61 (13.04-39.08)	13.39 (7.57-23.22)	12.02 (7.96-18.41)	8.40 (4.92-14.52)	31.50 (20.28-48.91)	21.42 (15.74-29.17)	16.23 (11.05-23.83)
23	25.28 (19.06-33.32)	16.70 (12.78-21.76)	8.36 (5.90-11.90)	32.95 (18.60-57.68)	20.07 (12.08-33.28)	15.35 (7.99-29.90)	29.31 (14.92-57.41)	16.72 (11.38-24.71)	13.17 (7.82-22.38)	64.59 (31.38-134.81)	29.55 (18.04-49.37)	24.84 (14.31-42.96)	14.38 (8.13-24.94)	12.85 (8.51-19.69)	9.01 (5.28-15.58)	31.89 (20.53-49.51)	21.60 (15.87-29.41)	16.37 (11.14-24.03)
24	25.78 (19.44-33.98)	17.04 (13.03-22.20)	8.53 (6.01-12.14)	36.70 (20.71-64.26)	21.88 (13.16-36.28)	16.95 (8.82-33.04)	30.62 (15.58-59.99)	17.87 (12.17-26.43)	14.24 (8.46-24.20)	73.56 (35.70-153.78)	32.14 (19.62-53.76)	27.29 (15.70-47.24)	15.46 (8.73-26.80)	13.74 (9.10-21.07)	9.66 (5.66-16.72)	32.25 (20.76-50.08)	21.76 (15.99-29.63)	16.49 (11.23-24.21)
25	26.28 (19.81-34.64)	17.37 (13.29-22.63)	8.70 (6.14-12.39)	40.89 (23.06-71.60)	23.84 (14.33-39.54)	18.71 (9.74-36.51)	31.94 (16.25-62.58)	19.11 (13.00-28.28)	15.39 (9.15-26.18)	83.77 (40.62-175.42)	34.96 (21.32-58.55)	29.98 (17.23-51.95)	16.61 (9.38-28.80)	14.69 (9.73-22.54)	10.36 (6.07-17.94)	32.59 (20.98-50.60)	21.91 (16.10-29.84)	16.61 (11.31-24.38)

Table 7. Growth rate of DBH (cm year^{-1}), TH (m year^{-1}) and MH (m year^{-1})*

Age	***H. brasiliensis***			***H. odorata***			***S. roxburghii***			***S. macrophylla***			***D. alatus***			***A. excelsa***		
(year)	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**	**DBH**	**TH**	**MH**
1	2.273	1.917	0.513	0.349	0.272	0.181	1.209	0.265	0.192	0.514	0.408	0.310	0.220	0.204	0.140	1.775	2.844	2.108
2	2.345	1.598	0.606	0.389	0.296	0.200	1.228	0.284	0.208	0.585	0.444	0.340	0.237	0.218	0.150	3.387	3.240	2.438
3	2.394	1.421	0.716	0.433	0.323	0.221	1.240	0.303	0.224	0.666	0.483	0.374	0.254	0.233	0.161	3.568	2.680	2.030
4	2.430	1.302	0.846	0.483	0.352	0.244	1.250	0.324	0.243	0.758	0.525	0.410	0.273	0.249	0.173	3.219	2.114	1.607
5	2.460	1.215	1.000	0.538	0.383	0.269	1.257	0.347	0.262	0.864	0.571	0.451	0.294	0.267	0.185	2.776	1.673	1.275
6	2.485	1.146	1.182	0.599	0.418	0.297	1.264	0.371	0.284	0.984	0.621	0.495	0.316	0.285	0.199	2.367	1.345	1.027
7	0.933	0.617	0.123	0.667	0.455	0.328	1.269	0.397	0.307	1.120	0.675	0.544	0.339	0.305	0.213	2.020	1.100	0.840
8	0.873	0.577	0.125	0.744	0.496	0.362	1.274	0.424	0.332	1.276	0.735	0.598	0.365	0.326	0.229	1.734	0.913	0.699
9	0.823	0.544	0.128	0.828	0.541	0.400	1.278	0.453	0.358	1.453	0.799	0.657	0.392	0.349	0.245	1.499	0.769	0.589
10	0.780	0.516	0.130	0.923	0.589	0.441	1.282	0.485	0.388	1.655	0.869	0.721	0.421	0.373	0.263	1.306	0.656	0.503
11	0.743	0.492	0.133	1.028	0.642	0.487	1.286	0.518	0.419	1.884	0.945	0.792	0.453	0.399	0.282	1.146	0.566	0.434
12	0.710	0.470	0.135	1.145	0.700	0.538	1.289	0.554	0.453	2.146	1.028	0.871	0.486	0.426	0.302	1.013	0.493	0.378
13	0.682	0.451	0.138	1.276	0.763	0.594	1.292	0.593	0.490	2.444	1.118	0.956	0.523	0.456	0.324	0.901	0.433	0.332
14	0.656	0.434	0.141	1.422	0.831	0.655	1.295	0.634	0.529	2.783	1.216	1.051	0.562	0.487	0.348	0.806	0.384	0.294
15	0.633	0.419	0.144	1.584	0.906	0.724	1.297	0.678	0.572	3.169	1.323	1.154	0.604	0.521	0.373	0.726	0.342	0.262
16	0.613	0.406	0.147	1.764	0.987	0.799	1.300	0.725	0.619	3.609	1.438	1.268	0.649	0.557	0.400	0.656	0.307	0.235
17	0.594	0.393	0.150	1.965	1.076	0.882	1.302	0.775	0.669	4.110	1.564	1.393	0.697	0.596	0.429	0.596	0.277	0.212
18	0.576	0.382	0.153	2.190	1.173	0.974	1.304	0.829	0.723	4.681	1.702	1.530	0.749	0.637	0.460	0.543	0.251	0.192
19	0.560	0.371	0.156	2.439	1.278	1.075	1.306	0.886	0.782	5.331	1.851	1.681	0.805	0.681	0.494	0.498	0.228	0.175
20	0.546	0.361	0.159	2.718	1.393	1.187	1.308	0.947	0.845	6.071	2.013	1.847	0.865	0.728	0.530	0.457	0.209	0.160
21	0.532	0.352	0.162	3.027	1.518	1.311	1.310	1.013	0.914	6.914	2.189	2.029	0.930	0.779	0.568	0.422	0.191	0.147
22	0.519	0.344	0.165	3.373	1.654	1.447	1.312	1.083	0.988	7.874	2.381	2.229	0.999	0.833	0.609	0.390	0.176	0.135
23	0.507	0.336	0.169	3.757	1.803	1.598	1.313	1.158	1.068	8.967	2.590	2.448	1.074	0.890	0.653	0.362	0.163	0.125
24	0.496	0.329	0.172	4.186	1.965	1.764	1.315	1.239	1.155	10.212	2.817	2.690	1.154	0.952	0.701	0.336	0.151	0.116

Table 8. Example of using prediction results to calculate the ecosystem services quantity and values for individual years

Species	At 10-year age						At 20-year age					
	Quantity (ha^{-1})			Value (USD ha^{-1})			Quantity (ha^{-1})			Value (USD ha^{-1})		
	CO$_2$ (tCO$_2$ eq)	O$_2$ (kg O$_2$)	Timber volume (m^3)	CO$_2$	O$_2$	Timber	CO$_2$ (tCO$_2$ eq)	O$_2$ (kg O$_2$)	Timber volume (m^3)	CO$_2$	O$_2$	Timber
H. brasiliensis	15.4	10725	118.5	433.194	5362.5	4399.5	18.9	10889.5	276.5	529.9	6560	10206.6
H. odorata	0.6	392.2	1.7	15.8	196.1	894.4	9.2	6431.2	40.1	259.8	3215.6	20872.1
S. roxburghii	1.3	931.4	4.6	37.6	465.7	2122.3	5.4	3790.1	41.6	153.1	1895	19305.6
S. macrophylla	2	1366	6.4	55.2	683	2644.4	47.9	3350.55	222.1	1347.1	16675	91145.5
D. alatus	0.2	112.3	0.7	4.5	56.2	190.7	1.1	787.5	6.1	31.8	393.7	1621.8
A. excelsa	4.2	2922.2	40.2	118	1461.1	13096.4	2.3	1570.8	92.5	63.4	785.4	301214

Note: The figures are in that particular individual year. We use the general practiced density of *H. Brasiliensis* at 475 trees ha^{-1} and five species of intercropping at 47 trees ha^{-1}. Carbon dioxide. The annual carbon dioxide sequestration ha^{-1} was calculated from this equation: (BIT x 0.47) x 3.67 (BIT; biomass increment, 0.47 is carbon conversion factor (Eggleston et al. 2014) and 3.67 is carbon dioxide conversion factor (Meepol 2010)). The price of carbon assumed the price of CO$_2$ European Emission Allowances (Insider incorporated 2020). Oxygen production. The oxygen production was calculated from this equation: BIT x 1.2 (BIT; biomass increment, 1.2; oxygen conversion factor) (Yolasiğmaz and Keleş 2009). The price of oxygen was the market sale price of oxygen from hospitals in Songkhla province (Sathing Phra Hospital 2020; Somdejprabororomrachineenart Natawee Hospital 2020). Timber. Timber volume was calculated from V = 0.42×BA×MH (V; timber volume, 0.42; coefficients of shape tree stem, BA; tree basal area at breast height and MH; tree merchantable height) (Magnussen 2004). The timber prices of economic forest trees were used according to the Royal Forest Department (2016), while the timber price of *H. brasiliensis* was from the Rubber Authority of Thailand (2019). The prices were adjusted using the consumer price index and the costs of logging were subtracted to derive the net value (economic forest trees logging costs were from Roongtawanreongsri et al. (2007), and *H. brasiliensis* was from the Rubber Authority of Thailand (2017). Biomass increment. The annual biomass increment was calculated from this equation: B_{t+1} - B_t (B; biomass, t; time), Biomass was calculated from the sum of aboveground and belowground biomass. Aboveground biomass was calculated from the equation in Tsutsumi et al. (1983): $W_s = 0.0509\ (DBH^2 \times TH)^{0.919}$, $W_b = 0.00893\ (DBH^2 \times TH)^{0.977}$, $W_l = 0.0140\ (DBH^2 \times TH)^{0.669}$ and $W_t = W_s + W_b + W_l$. Belowground biomass calculated from this equation: $W_r = W_t \times 0.24$ (DBH; diameter at breast high, TH; total height, W_s: stem biomass, W_b; branch biomass, W_l; Leaf biomass, W_t; aboveground biomass, W_r; belowground biomass and 0.24; root/shoot ration in tropical zone (Cairns et al. 1997). The exchange rate was 1 USD = 32.4 Baht on 27 March 2020 (Bank of Thailand 2020).

Table 9. Comparison between the models' prediction and the observed data from other studies

Tree	Age	Area (province)	References	Result of other studies		Result of prediction in this study	
				DBH (cm)	TH (m)	DBH (cm)	TH (m)
H. brasiliensis	5.5	Songkhla	Booranatam et al. (2003)	14.78	-	13.43	-
	6.5	Krabi		14.90	-	14.18	-
	9	Yala		19.39	-	16.45	-
S. macrophylla	4.5	Krabi	Booranatam et al. (2003)	8.12	-	5.83	-
	5.5	Yala		9.90	-	6.64	-
	7	Songkhla		9.08	-	8.07	-
	9[1]	Prachuap Khiri Khan	Sathapong (1970)	10	10.20	10.47	9.12
A. excelsa	5.5	Yala	Booranatam et al. (2003)	9.62	-	13.47	-
	7	Songkhla		9.08	-	17.17	-
	9.5	Yala		10.75	-	21.70	-
	5[2]	Nakhon Si Thammarat	Phartnakorn and Jirasuktaveeku (1998)	15.07	10.30	12.03	11.29
	8[2]			21.39	13.41	19.2	15.40
	11[2]			25.08	15.89	23.7	17.74
H. odorata	17[3]	Nakhon Ratchasima	Sakai et al. (2010)	14.47	11.60	17.23	11.98
D. alatus	20[4]	Nakhon Ratchasima	Sakai et al. (2010)	11.90	10.95	11.59	10.51

Note: [1]Monoculture *S. macrophylla*, [2]Monoculture *A. excelsa,* [3]*H. odorata* planted with *Senna siamea* (Lam.) Irwin & Barne., [4]*D. alatus* planted with *Leucaena leucocephala* (Lam.) de Wi

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