

# Facilitating objective forest land use decisions by site classification and tree growth modeling: a case study from Vietnam

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Onsite information pertaining to forest growth potential is a significant prerequisite for selecting suitable forest plantation locations and safeguards sustainable timber production and income generation. In the scope of forest landscape restoration, the selection of the most suitable sites for reforestation remains a major issue. The current study introduces an operational, objective, and straightforward methodology for the identification and prioritization of sites that are suitable for forest plantations. The methodology is based on an approach that combines land use suitability assessment with site-specific growth and yield predictions. The land use suitability assessment is based on a methodological framework presented by the Food and Agriculture Organization (FAO). In a study area in Vietnam four different suitability classes are defined for the species *Acacia mangium* (*A. mangium*). Field assessments in existing *A. mangium* plantations were utilized to develop yield models. Among the Korf, Gompertz, and Chapman-Richards growth equations Korf performed the best for all suitability classes. Prioritization of sites is realized by the analytical hierarchy process (AHP). Our study offers a pragmatic approach for selecting the most suitable sites for large-scale forest restoration activities. Integrating growth and yield predictions supports reforestation practices and promotes sustainable timber production.

**Keywords:** *Acacia mangium*, Suitability, Analytical Hierarchy Process, Volume Growth, Vietnam

## Introduction

A net annual decrease in forest area of 3.3 million ha per year was recorded in the period between 2010 and 2015, but planted forests increased by a net 3.1 million ha per year and now cover 7% of the global forest area (FAO 2015a). Afforestation programs and plantation forestry generally strive to satisfy timber demand and compensate for deforestation. According to Borges et al. (2014) the global timber volume produced in planted areas will increase from 1.4 billion m<sup>3</sup> in 2005 to 1.7 billion m<sup>3</sup> in 2030. Forest Landscape Restoration (FLR) is an initiative aimed at the reduction of degraded land through the restoration by multi-functional forest ecosystems and the improvement of forest growth quality in the landscape for the both people and biodiversity (Mansourian 2017).

Globally, 30% of the land surface is covered by forests which store 45% of the terrestrial carbon (Bonan 2008). Deforestation reduces the forest landscape and diminishes carbon stocks. Deforestation and forest degradation cause 17-25% of the annual anthropogenic greenhouse gas emissions and remain the main drivers of global warming (Khuc et al. 2018). Many activities have been implemented to reduce deforestation and forest degradation especially in developing countries. Under the United Nations Program on Reducing Emission from Deforestation and Forest Degradation (REDD+) financial incentives for implementing large-scale FLR programs have been provided to 64 developing countries with the objective to conserve forest carbon stocks, promote sustainable forest management and boost forest carbon

stocks (Neupane et al. 2017, Chazdon & Guarigueta 2018).

Afforestation and reforestation contribute to an increase in forest cover and a rise in forest carbon stocks worldwide (FAO 2010). Furthermore, many countries, including Vietnam, are responding to the New York Declaration on Forests, by cutting the loss of natural forest in half by 2020, attempting to stop the loss of natural forest by 2030, and by reducing annual emission by 4.5 to 8.8 billion tonnes of CO<sub>2</sub> through forest protection and restoration. The extension of forest areas through afforestation and reforestation along with improved forest productivity in forest plantations are solutions for contributing to the successful restoration of globally degraded and deforested land as well as the mitigation of global greenhouse gas emissions as called for by the New York Declaration and Bonn Challenge (<https://forestdeclaration.org>, <https://www.bonnchallenge.org>).

Vietnam is committed to increasing its forest cover. Since 1990 the forested area has continuously been enlarged and reached 41.5% of total land area in 2014. From 1990 to 2015 the area of forest plantations increased on average by 107,800 hectares annually (FAO 2015b). Currently, more than 3.5 million hectares are covered by forest plantations. Most of the timber grown in forest plantations is used for the production of pulp and paper. Many major national programs have been initiated for

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afforestation and reforestation purposes (De Jong et al. 2006). The national afforestation program 661, also called the Five Million Hectare Reforestation Program (5MHRP), implemented between 1998 and 2010 focused on reforesting degraded land (Hung et al. 2011). One of the main incentives for increased forest plantation expansion are the government policies on forest land allocation (Clement & Amezaga 2009). By 2020 forest plantations are estimated to cover 4.1 million hectares (Pistorius et al. 2016).

Land suitability assessments aim at identifying the most appropriate spatial pattern for future land use in order to meet specific demands (FAO 1984, 2007). Land suitability assessments are essential prerequisites for establishing forest plantations (Ryan et al. 2002). In the current study, site condition classification for growing *A. mangium* is based on a land suitability evaluation technique developed by FAO (1984). Timber production is selected as the land use of interest and land use suitability analysis focuses on the identification of suitable locations for afforestation with *A. mangium* to allow for sustainable timber production. This method matches the ecological requirements of *A. mangium* with site conditions. Land suitability classification serves the estimation of timber growth.

Timber growth depends on site conditions and, inversely, produced timber growth reflects site productivity. Timber volume growth depends on natural factors such as soil properties, climate, and topography and can be considered an indicator directly linked to site productivity (Skovsgaard & Vanclay 2008). In addition, timber volume growth is also considered an indicator of sustainability. Taking into account site-dependent growth patterns, land suitability classification for *A. mangium* forest plantations is combined with a site-specific growth model in order to obtain reliable information on potential timber production.

Vietnam is meeting the challenges of sustainable forest development in rural areas. High population numbers and the associated poverty as well as the dependence of the poorest sections of the population on forest resources represent special challenges for the development of a sustainable forest economy. According to Pham et al. (2012), in Vietnam 25 million forest-dependent people earn 20% of their income from forest resources. In addition, the demand of the wood-processing industry is constantly increasing due to the country's growing economy. On the other hand, there is only low profit growth and low productivity in the plantation economy, which is why there is an urgent need for action here. The selection of suitable areas for growing forest plantations is a crucial issue for the further development of the forest and timber sector in Vietnam, especially given the current situation of limited land availability. Finding suitable plantation

areas is also key to meeting the demand for sustainably produced timber, ensuring the long-term success of forest industries, increasing local incomes and contributing to poverty alleviation. Therefore, the overall objectives of this study provide technical guidance in site selection and on the readiness of FLR under sustainable forest management initiatives.

The specific objectives of the study are: (i) to identify site suitability and (ii) to identify site-specific timber growth as parameters to select sites for the establishment of forest plantations.

## Materials and methods

### Study area and species

Thai Nguyen Province is located in North-eastern Vietnam and covers an area of slightly more than 350,000 ha, with 87,000 ha of planted forests and 94,000 ha of natural forests. The elevation ranges from about 50 m to more than 900 m a.s.l. The slope of the terrain varies between 0 and more than 35 degrees. The mean annual temperature is approximately 24 °C and total annual precipitation is about 1700 mm (Anh et al. 2011).

In the study area, forests are classified as production, protection and special-use forests. The main objectives of the production forest are to provide timber, non-timber forest products in conjunction with environmental protection. In the recent years, there has been an increase in demand for timber from forest plantations, while the timber supply from forest plantations is probably not sufficient to keep pace with the increasing timber demand. Thai Nguyen Province was selected to conduct the research to enhance effective utilization of forest land through selecting suitable forest lands for forest plantations.

The study focuses on commercial forest plantations that supply timber to be processed in wood mills. The study species is *Acacia mangium* Willd. This species, which is also known by its local name *Keo tai tuong*, is one of the fastest-growing tree species in Vietnam (Sein & Mitlöhner 2011), and belongs to the family Leguminosae, sub-family Mimosoideae. The species originates from the humid tropical forests of Northeastern Australia, Papua New Guinea, and the Molucca Islands in Eastern Indonesia (Krisnawati et al. 2011). According to Harwood & Nambiar (2014), *Acacia* plantations in Vietnam (e.g., *A. auriculiformis*, *A. mangium*, and a hybrid of *A. auriculiformis* and *A. mangium*) covered around 1.1 million ha in 2013, of which 600,000 ha were stocked by *A. mangium* and mainly located in North Vietnam. In the study area, almost all of the harvested *A. mangium* timber is used to produce woodchips and pulpwood as raw materials for domestic use and export.

Desirable properties of *Acacia mangium* include rapid growth, good wood quality and tolerance to a variety of soils and envi-

ronments. It grows well on lateritic soils with high concentrations of iron and aluminum oxides, but is intolerant to saline conditions and shade. *Acacia* trees fix atmospheric nitrogen so that, in contrast to *Eucalyptus*, they increase the amount of nitrogen in the soil. Good management helps to minimise soil loss and fertility decline (Krisnawati et al. 2011).

### Procedure of land suitability evaluation

We implemented a land suitability classification based on the FAO framework (FAO 1984). The physical land suitability evaluation focuses on growth conditions for *A. mangium* and does not consider socio-economic criteria. A land suitability assessment is performed in three steps.

#### Step 1: Selection of factors for bio-physical land suitability evaluation

Factors to be utilized for the assessment of land suitability should be readily available to forest managers (Battaglia & Sand 1998) and have a close relationship to forest productivity. The ecological requirements of *A. mangium* presented by Krisnawati et al. (2011) were used to identify three factors, which are further defined by attributes, for the assessment of land suitability for establishing plantations:

- Soil properties (soil type, soil depth): soil properties were derived from the digital soil map provided by the Vietnam Academy of Agriculture Sciences (VAAS). The map was created in 2005 and includes soil type and soil depth information.
- Topography (elevation, slope): a digital elevation model (DEM) was obtained from the Shuttle Radar Topographic Mission (SRTM) at a resolution of 30 × 30 m (downloaded from <http://srtm.csi.cgiar.org>) and was provided by the Consortium for Spatial Information (CSI).
- Climate regime (mean annual rainfall): climatic information was provided by the Vietnam Institute of Meteorology, Hydrology and Climate Change (<http://www.imh.ac.vn>). Rainfall information was obtained based on the 15 years (from 2000 to 2014) of observations at three weather stations and 11 rainfall stations. Spatial interpolation of mean annual rainfall was implemented by applying inverse distance weighting (IDW) method in ArcGIS® 10.2.2 platform (ESRI, Redlands, CA, USA). Mean annual rainfall map is represented in Fig. 1.

#### Step 2: Combining the three factors to suitability classes

Land use suitability analysis aims to identify the most appropriate future land use to meet specific demands (FAO 1984, 2007). Classes are determined for each factor based on how a specific tree species behaves under certain environmental conditions. Land suitability evaluations (FAO 1984) define suitability is the fitness of a given type of land for a defined use. Four classes for land suitability classification are

applied:

- S1 (Highly suitable): land having negligible or slight limitations affecting site productivity (productivity class 1), and with negligible or slight management limitations or degradation hazards;
- S2 (Moderately suitable): land having moderate limitations affecting site productivity (productivity class 2), or land having higher productivity but with moderate management limitations or degradation hazards;
- S3 (Marginally suitable): land having severe limitations affecting site productivity (productivity class 3), or land having higher productivity but with severe management limitations or degradation hazards;
- Un (Unsuitable): land having severe limitations affecting site productivity (productivity class 4), or land having higher productivity but with very severe management limitations or severe to very degradation hazards.

Based on a comparison between tree species requirements and site conditions, ecological factors were allocated to respective suitability classes. The evaluation was supported by the additional consultations of four local experts, who provided field knowledge pertaining to forest growth, soil sciences, and suitable forest site assessment for the main tree species in Vietnam. The experts were selected from the fields of science and forestry practice and are considered to be the most experienced in the cultivation of *A. mangium*.

**Step 3: Determination of scores and weights of land suitability for *A. mangium***

Land suitability classes reflect the degree of suitability. In order to utilize the suitability classes identified in Step 2 for the prioritization of individual sites for reforestation, a ranking has to be introduced. By a pragmatic decision it was decided to introduce scores ranging from 1 to 4. A higher score was assigned to higher suitable land (suitability class) for growing *A. mangium* (see Tab. S1 in the Supplementary materials for questionnaires for suitability classes determination for *A. mangium* and pair wise comparison):

- Unsuitable class: score equals 1;
- Marginally suitable class: score equals 2;
- Moderately suitable class: score equals 3;
- Highly suitable class: score equals 4.

Scoring of individual sites has to take into account that each factor has a different effect on tree growth and forest productivity. Therefore, the contribution of individual factors and attributes of factors on the decision-making process was assessed by means of the AHP process. The AHP is included in the family of multi-criteria decision-making techniques (Nekhay et al. 2009) and is utilized to assign weights for standardization of criteria maps based on expert knowledge (Murayama 2012, Feizizadeh et al. 2014, Mishra et al. 2015, Kangas et al. 2015). After gaining information

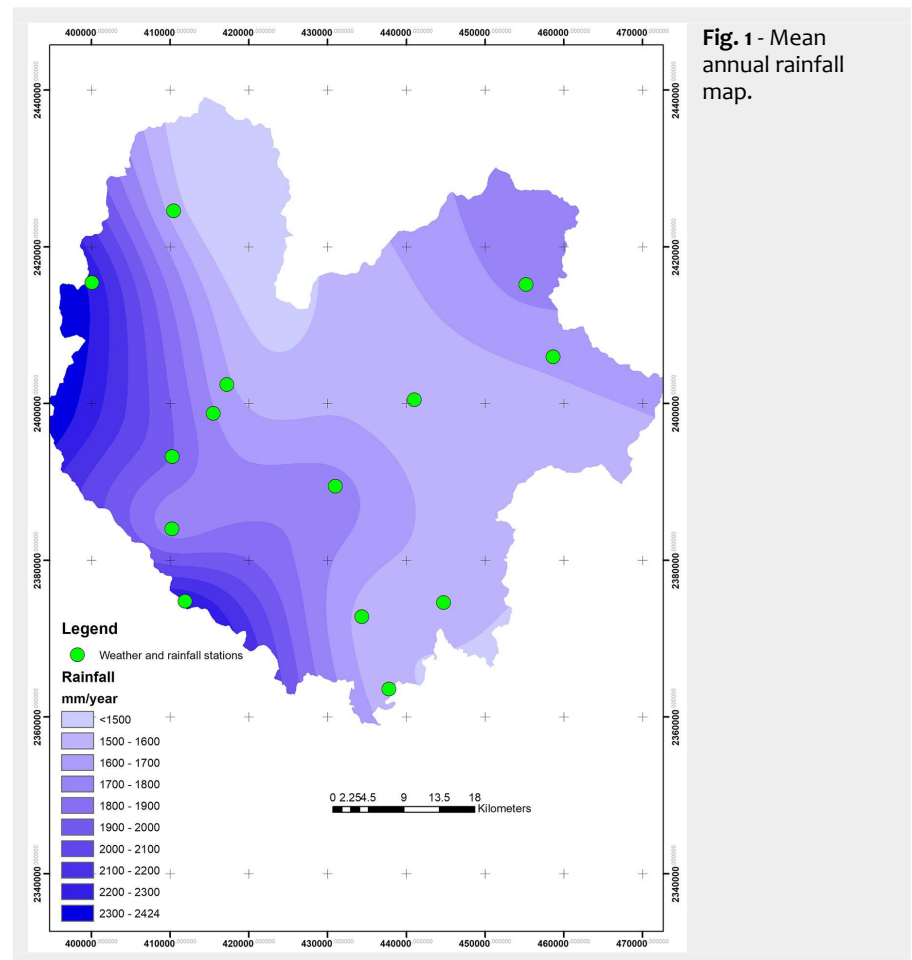


Fig. 1 - Mean annual rainfall map.

for site suitability and bio-physical factors (Step 1) and attributes assigned to each individual suitability class from forestry expert consultations (Step 2), AHP was used to determine the weight of each factor and each attribute by regarding soil properties, topography and rainfall regime. The experts were asked to rank the individual factors and attributes with respect to their importance for tree growth. The ranking was performed by a pair-wise comparison.

In AHP methodology, pairwise comparisons show forestry experts' preferences by comparing two factors at a time. AHP methodology was implemented in four main steps (Vaidya & Kumar 2006):

- Taking consideration of a hierarchy of different factors (soil properties, topography, climate);
- Using pairwise matrix to assess and assign the importance of each factor with scale ranges from 1 to 9. According to Saaty & Vargas (2012), preferences are expressed by numerical values of 1, 3, 5, 7 and 9, respectively, with 2, 4, 6 and 8 as intermediate values between adjacent scale values. For example, 1 implies "least valued than" and 9 implies "absolutely more important than" in the pairwise comparison matrix (Saaty & Vargas 2012).
- Determining eigenvalue  $\lambda_{max}$  of the reciprocal ratio matrix, eigenvector, consistency ratio (CR) based on consistency index (CI) and random index (RI) and the

normalized value for each criteria/alternative;

- Checking the satisfactory of consistency ratio (CR) in order to make decisions based on the normalized values for criteria and determine the final overall rating. Aggregation Individual Judgment (AIJ) is considered a unique mode to combine individual judgments into group judgment (Saaty & Peniwati 2008). AIJ matrices are calculated as (eqn. 1):

$$A = \sqrt[m]{x_1 \cdot x_2 \cdot \dots \cdot x_m} \quad (1)$$

where  $x_i$  are judgments of individual  $i$ ,  $i = \{1, \dots, m\}$ ,  $A$  is the aggregation individual judgment by geometric mean.

To ensure that the decision makers' judgments of are consistent, the consistency ratio (CR) and consistency index (CI) were applied, which are defined as (eqn. 2, eqn. 3):

$$CR = \frac{CI}{RI} \quad (2)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

where  $\lambda_{max}$  is the maximum eigenvalue of the normalized comparison matrix,  $\lambda_{max} \geq n$ ,  $RI$  is a Random Index for the number of factors compared in a matrix, appropriate consistency index, corresponds index of consistency for random judgments, and  $n$  is the number of factors being compared

( $n = 3$ ,  $RI = 0.52$  – Saaty & Vargas 2012).  $CI$  estimates the level of consistency with respect to the entire comparison process.  $CRs$  less than or equal to 0.1 (10%) indicate consistent assessments of decision-makers, for  $CRs > 0.1$  the individual criteria have to be re-examined (see Tab. S1 in the Supplementary materials for pair-wise comparisons for factors by experts and aggregation of individual judgments).

Each attribute was mapped according to the attributes mentioned under step 1 (soil type, soil depth, elevation, slope, and rainfall). Each input raster layer was weighted according to its proportional influence given the constraint that the sum of the percentage influence weights for all the raster map (factors and attributes) is equal to 1 (see Tab. S1 in the Supplementary materials for weights of each attribute and each factor).

The individual attribute maps were combined by the weighted linear combination method (WLC) in a GIS environment (raster calculator tool in ArcGIS). WLC was developed by Eastman et al. (1995). The higher the combined value achieved by weighing in the cell, the more suitable it is for *A. mangium*. The final score was converted to each suitability class including S1, S2, S3 and Un for areas unsuitable for afforestation. The final score of the land suitability in each suitability class is defined as (eqn. 4):

$$S = \sum W_i \cdot X_i \tag{4}$$

where  $S$  is the final score/suitability,  $W_i$  is the weight of factor  $i$ , and  $X_i$  is the score of class  $i$ .

### Modelling productivity

Productivity is an ultimate indicator of a tree's reaction to its environmental conditions. The most widely used direct measure of forest site productivity is volume. Productivity ( $m^3 ha^{-1}$ ) in each suitability class was assessed based on data collection by a forest inventory in the research area.

### Sample plot design

A forest survey aims to supply data for fitting growth functions of studied species and establishing a potential productivity map. Through forest inventories, information on the quality and quantity of forest resources such as forest growth, area, and species identification can be recorded (Köhl et al. 2006). A concentric circular plot design, with three different plot radii was applied:

- $r_1 = 5.64$  m / area of 100  $m^2$  for the trees with  $DBH > 0$  cm;
- $r_2 = 7.98$  m / area of 200  $m^2$  for the trees with  $DBH \geq 5$  cm;
- $r_3 = 12.62$  m / area of 500  $m^2$  for the trees with  $DBH \geq 12$  cm.

The  $DBH$  all trees within a plot was measured using a diameter tape. On ten trees (closest to the center point of plot) per plot tree height was recorded using a Criterion RD 1000 laser instrument.

### Sample plot allocation

Based on a map that presents the allocation of the studied species with respect to age classes and suitability classes, the number of sample plots was determined in line with the percentage of stands that each suitability class occupied (S1: 40%, S2: 30%, S3: 30%). A total of 152 concentric circular sample plots was laid out following a sys-

tematic selection. All stand ages from 1 to 9 years were covered.

### Calculation of stand variables

The data assessed on the 152 concentric plots was utilized to describe the relationship between tree height and diameter at breast height by a linear model (Pretzsch 2009 – eqn. 5):

$$h = a \cdot DBH + b \tag{5}$$

where  $a$ ,  $b$  are coefficients of the model,  $h$  is the total height of tree (m), and  $DBH$  is the diameter at breast height (cm).

The model was used to estimate height of mean quadratic diameter tree in relation to the quadratic mean diameter calculated with the following equation for each concentric plot (eqn. 6, eqn. 7):

$$h_{gi} = a \cdot d_{gi} + b \tag{6}$$

$$d_{gi} = \sqrt{\frac{40000 g_i}{\pi n_{si}}} \tag{7}$$

where  $a$  is the line slope,  $b$  is intercept,  $d_{gi}$  is the quadratic mean diameter (cm) at plot in the plot  $i$ ,  $g_i$  is the basal area ( $m^2 ha^{-1}$ ) in the plot  $i$ ,  $h_{gi}$  is the height of mean quadratic diameter tree in the plot  $i$ ,  $n_{si}$  is the stocking density (trees  $ha^{-1}$ ) in the plot  $i$ .

The parameters  $d_{gi}$  and  $h_{gi}$  were utilized to calculate the volume of live stems per hectare (eqn. 8):

$$V = n_s \left( \frac{\pi}{4} \right) \cdot d_{gi}^2 \cdot h_{gi} \cdot f \tag{8}$$

where  $f$  is the tree form (commonly used for *A. mangium* in Vietnam:  $f = 0.49$  – Sein & Mitlöchner 2011).

### Modelling volume growth for suitability classes

The growth model is based on observations of growing stock volumes to predict the potential production of forest plantations. By using growth models, we can explore stand conditions and determine the harvesting time needed for maximizing timber production. Many studies have applied empirical functions (Tewari et al. 2002, Berrill 2004, Tewari & Kumar 2005, HUU-DUNG & YEO-CHANG 2012, Steward et al. 2014). Generally, the overall shape of the curve is sigmoid (Amaro et al. 2003, Burkhardt & Tomé 2012). The data from the concentric plots were used to model yield curves (Pretzsch 2009) as described by Korf (1939 – eqn. 9), Gompertz (1825 – eqn. 10), and Chapman-Richards (1961-1959 – eqn. 11):

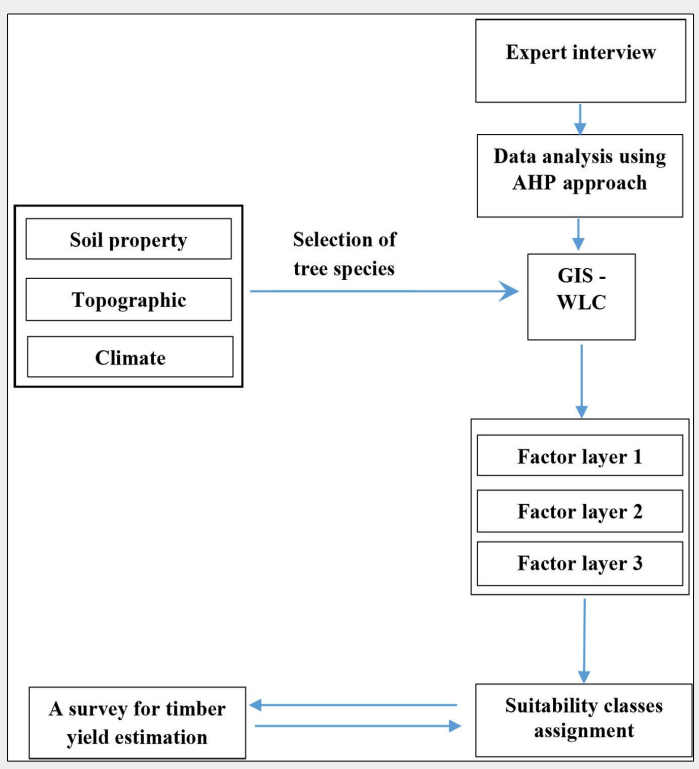
$$V = a_0 \cdot e^{(-a_1 \cdot A^{-a_2})} \tag{9}$$

$$V = a_0 \cdot e^{(-a_1 \cdot e^{-a_2 \cdot A})} \tag{10}$$

$$V = a_0 \left( 1 - e^{-a_1 \cdot A} \right)^{a_2} \tag{11}$$

where  $a_0$ ,  $a_1$ , and  $a_2$  are the parameters to be estimated (asymptote, slope, and posi-

Fig. 2 - Steps of the proposed methodology.



tion of inflection point, respectively),  $V$  is the standing volume of live trees per hectare at age  $A$ ,  $A \in (1, i)$ .

Models were developed by means of R software (R Core Team 2013). The coefficient of determination ( $r^2$ ), the root mean square error (RMSE) and Akaike's information criterion (AIC) were used to measure the goodness-of-fit per suitability class.

Steps of the proposed methodology are represented in Fig. 2.

**Results**

**Assignment of suitability classes for *A. mangium***

Tab. 1 presents the judgement of the consulted experts on the impact of individual bio-physical attributes for growth of *A. mangium*. According to the experts, soil types Rhodic ferralsol (Fk), Ferralic Acrisol (Fp), or Dystric gleysol (D), soil depth  $\geq 100$  cm, elevation  $< 200$  m a.s.l., slope gradient between 0 and 15 degrees and annual rainfall above 2000 mm favour the growth of *A. mangium*.

The aggregation of the four judgments was calculated to obtain the eigenvector and give the results of weighting calculation based on revised power (Tab. 2).

The consistency analysis presented in Tab. 2 was performed using the normalized matrix of criteria and final weights of criteria. The results illustrate that the consistency index (CI) for paired criteria concerning the impact of different factors on land suitability was 0.003 (0.3%) and the consistency ratio (CR) was 0.005, which was acceptable as it is smaller than the 10% threshold proposed by Saaty & Vargas (2012). Soil properties were identified as the most important factor, followed by topographic and climate factors. Based on the principle of the WLC, the raster calculator tool in an ArcGIS environment was utilized to combine raster inputs with different weights of factors.

The result indicates that the largest area of forest land with respect to potential suitability for forest plantations with *A. mangium* belongs to the moderately suitable class (S2: 65.20%), followed by the highly suitable class (S1: 24.18%), marginally suitable class (S3: 5.82%), and unsuitable class (Un: 4.8%). A map of suitability locations for growing *A. mangium* is represented in Fig. 3.

**Forest stand growth**

**Stand variables according to suitability classes**

The survey covered stand ages between 1 and 9 years and a mean stand age of 5 years for all three suitability classes (Tab. 3). Likewise, the stocking density is nearly the same among the suitability classes. Basal area, quadratic mean diameter, stand height, and volume show an increase with site quality indicating higher productivity.

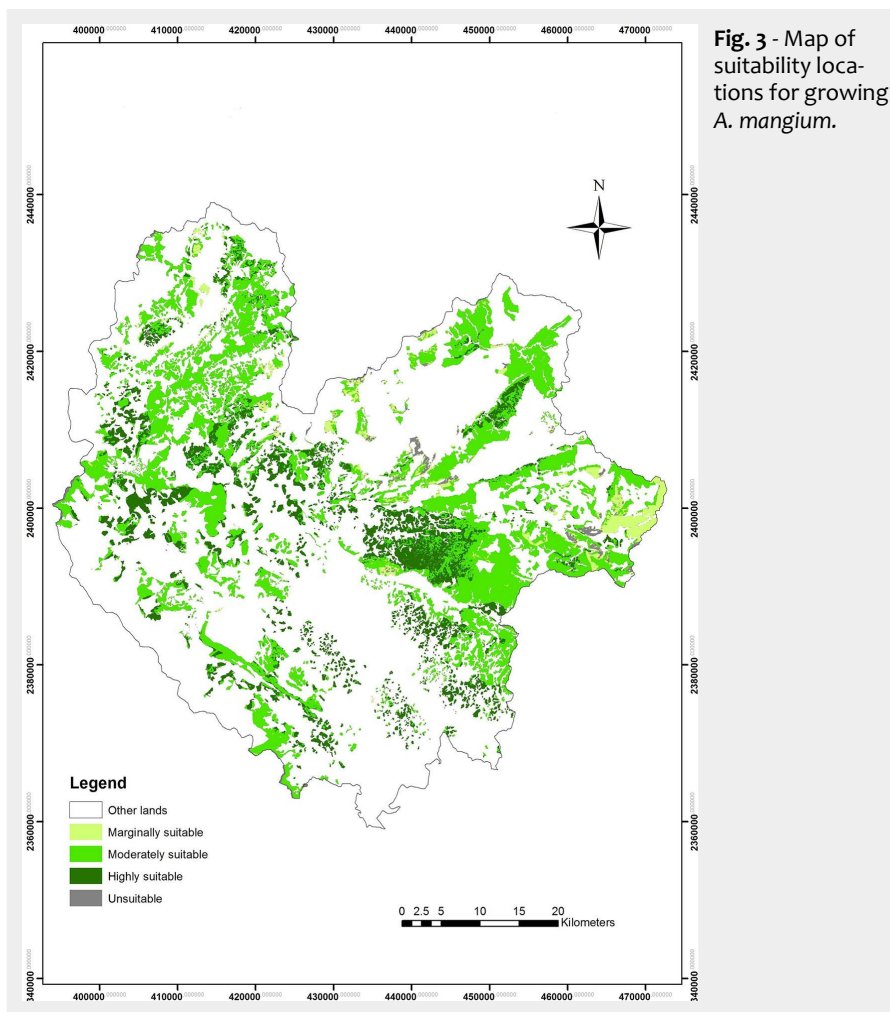
The relationships between quadratic

**Tab. 1** - Attributes of factors for determination of suitability classes for *A. mangium*. (\*) Soil types: (Fk) Rhodic ferralsols developed on bases and acid magma rock; (Fp) Ferralic Acrisols, formed by the feralite process, is ancient alluvial soil; (D) Dystric gleysols; (Fs) Yellowish red soil on metamorphic and sedimentary rock; (Fa) Ferralic Acrisols is yellowish red soil developed on acid magma, formed by the feralite process; (Fv) Rhodic ferralsols developed on limestone; (Fq) Yellowish red soil developed on sandstone; (Rk) Chromic luvisols; (Ha) Humic ferralsols developed on acid magma rock.

| Site condition  | Forestry land suitability |                          |                          |                 |
|---|---------------------------|--------------------------|--------------------------|-----------------|
|   | Highly suitable (S1)      | Moderately suitable (S2) | Marginally suitable (S3) | Unsuitable (UN) |
| Soil type*  | Fk, Fp, D                 | Fs, Fa, Fv               | Fq, Rk, Ha               | Karst           |
| Soil depth (cm)   | $\geq 100$                | $\geq 70-100$            | $\geq 50-70$             | 50              |
| Elevation (m a.s.l.)  | $< 200$                   | 200-400                  | 400-700                  | $>700$          |
| Slope gradient (degree)   | 0-15                      | 15-25                    | 25-35                    | $>35$           |
| Mean annual rainfall (mm/year)                                  | 2000-2400                 | 1500-2000                | 1300-1500                | $< 1300$        |
| Score of each variable category for land suitability assessment | 4                         | 3                        | 2                        | 1               |

**Tab. 2** -  $A_{ij}$  for pair-wise comparison matrix of four experts ( $\lambda_{max} = 3.005$ ; CI = 0.003; RI = 0.52; CR = 0.005).

| -               | Soil properties | Topography | Climate | Eigenvector | Weight (Revised power) |
|-----------------|-----------------|------------|---------|-------------|------------------------|
| Soil properties | 1               | 2.20       | 3.00    | 0.550       | 0.556                  |
| Topography      | 0.45            | 1          | 1.70    | 0.280       | 0.272                  |
| Climate         | 0.33            | 0.59       | 1       | 0.170       | 0.172                  |

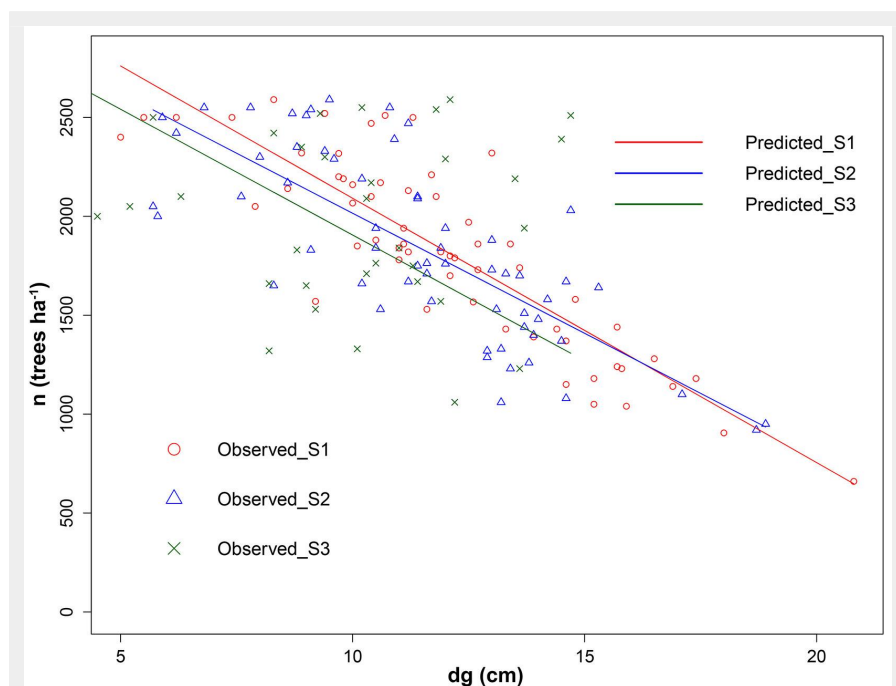


**Fig. 3** - Map of suitability locations for growing *A. mangium*.

**Tab. 3** - Summary of stand attributes for suitability classes S1, S2, and S3.

| Suitability class      | No. of plots | Statistics | Variables |  |   |                              |                                     |   |
|------------------------|--------------|------------|-----------|--|---|------------------------------|-------------------------------------|---|
|                        |              |            | Age (yrs) | Stocking density (trees ha <sup>-1</sup> ) | Basal area (m <sup>2</sup> ha <sup>-1</sup> ) | Quadratic mean diameter (cm) | Stand mean height (h <sub>g</sub> ) | Volume (m <sup>3</sup> ha <sup>-1</sup> ) |
| Highly suitable S1     | 59           | Min        | 1         | 660  | 4.8   | 5.0                          | 5.6                                 | 13.1                                      |
|                        |              | Max        | 9         | 2590                                       | 30.6  | 20.8                         | 17.0                                | 235.6                                     |
|                        |              | Mean       | 5         | 1823                                       | 19.5  | 12.0                         | 12.6                                | 125.7                                     |
| Moderately suitable S2 | 60           | Min        | 1         | 920  | 5.2   | 5.7                          | 4.7                                 | 12.2                                      |
|                        |              | Max        | 9         | 2590                                       | 34.5  | 18.9                         | 16.9                                | 262.2                                     |
|                        |              | Mean       | 5         | 1837                                       | 18.3  | 11.5                         | 11.8                                | 112.3                                     |
| Marginally suitable S3 | 33           | Min        | 1         | 1000                                       | 2.6   | 3.6                          | 3.0                                 | 3.8                                       |
|                        |              | Max        | 9         | 2800                                       | 27.5  | 14.7                         | 15.1                                | 173.5                                     |
|                        |              | Mean       | 5         | 1905                                       | 14.7  | 10.0                         | 10.5                                | 81.8                                      |

mean diameter and tree number per hectare are presented in Fig. 4. In all three suitability classes (S1, S2, S3) the relationship is negatively correlated. The relationships between quadratic mean diameter and tree number per hectare in different



**Fig. 4** - Relationship between quadratic mean diameter and tree number per hectare in different suitability classes.

**Tab. 4** - The fitted models for *A. mangium*.

| Suitability class | Function         | r <sup>2</sup> | RMSE  | AIC    | Number of plots |
|-------------------|------------------|----------------|-------|--------|-----------------|
| S1                | Korf             | 0.873          | 18.23 | 517.99 | 59              |
|                   | Gompertz         | 0.870          | 18.49 | 518.19 | 59              |
|                   | Chapman-Richards | 0.872          | 18.26 | 519.69 | 59              |
| S2                | Korf             | 0.766          | 26.10 | 569.66 | 60              |
|                   | Gompertz         | 0.766          | 26.09 | 569.62 | 60              |
|                   | Chapman-Richards | 0.766          | 26.08 | 569.56 | 60              |
| S3                | Korf             | 0.926          | 11.73 | 264.01 | 33              |
|                   | Gompertz         | 0.926          | 11.68 | 263.84 | 33              |
|                   | Chapman-Richards | 0.926          | 11.70 | 263.93 | 33              |

suitability classes were fitted by a linear model. The resulting functions are similar but shifted to the right into higher diameter classes with improving suitability calls.

Class S1 (r<sup>2</sup> = 0.751; P < 0.001 – eqn. 12):

$$n = -133.66 \cdot dg + 3428.90 \quad (12)$$

Class S2 (r<sup>2</sup> = 0.594; P < 0.001 – eqn. 13):

$$n = -121.41 \cdot dg + 3229.74 \quad (13)$$

Class S3 (r<sup>2</sup> = 0.667; P < 0.001 – eqn. 14):

$$n = -127.16 \cdot dg + 3177.06 \quad (14)$$

where n is the number of trees per ha (trees ha<sup>-1</sup>), and dg is the quadratic mean diameter (cm).

Fig. 5 shows the per hectare volume over stand age. Stand volumes vary not only with stand age but also with suitability classes. Volumes are consistently larger in higher suitability classes, which supports the applicability of the suitability classification found for the study area. Differences of volume growth of *A. mangium* between the three suitability classes were significant (Kruskal-Wallis test,  $\chi^2 = 15.74$ , P < 0.001).

**Yield function**

The yield model describes the productivity of the three levels of suitability classes. For the suitability class “unsuitable” no model was developed because data was not collected. Each suitability class resulted in a different age-related yield (Fig. 5). Three types of models were utilized to fit volume yield as a function of stand age.

RMSE, AIC and r<sup>2</sup> values indicate a good fit for all models and suitability classes (Tab. 4). The Korf function obtained slightly higher values for r<sup>2</sup>, hence, the Korf functions of the respective suitability classes were selected to perform volume yield of *A. mangium* according to age. They show volume yield of *A. mangium* as follows (eqn. 15, eqn. 16, eqn. 17):

$$V(S_1) = 5488.675 \cdot e^{-5.662 \cdot A^{-0.252}} \quad (15)$$

$$V(S_2) = 2225.187 \cdot e^{-5.242 \cdot A^{-0.338}} \quad (16)$$

$$V(S_3) = 479751.862 \cdot e^{-10.945 \cdot A^{-0.145}} \quad (17)$$

The shapes of the volume curves indicate clear differences between the best and the worst suitability class (Fig. 6), which clearly shows differences in site-related yield.

Tab. 5 presents volume and mean annual increment (MAI) for stand age and suitability class as obtained by the Korf function. In S1 a maximum MAI of 25.3 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> is found at age 4 years. In S2 the maximum MAI (21.2 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>) is found at age 5. In S3 the maximum MAI (20.0 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>) is found at age 18. MAI consistently increases with stand suitability; the MAI ranges of individual suitability classes do not overlap. Hence, the selection of suitability classes has a decisive influence on timber produc-

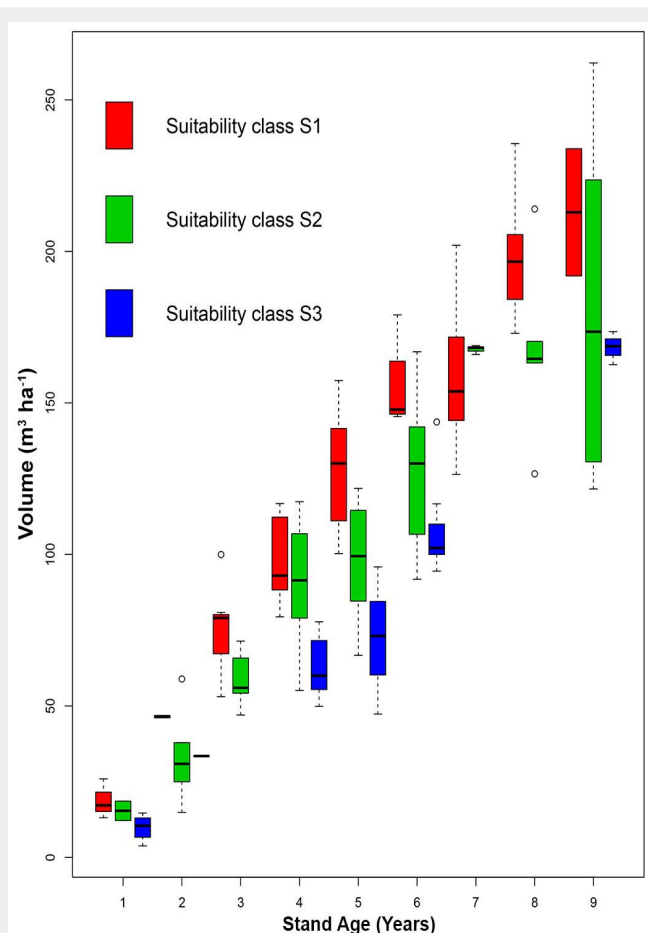


Fig. 5 - Distribution of volume per hectare according to age by different suitability classes.

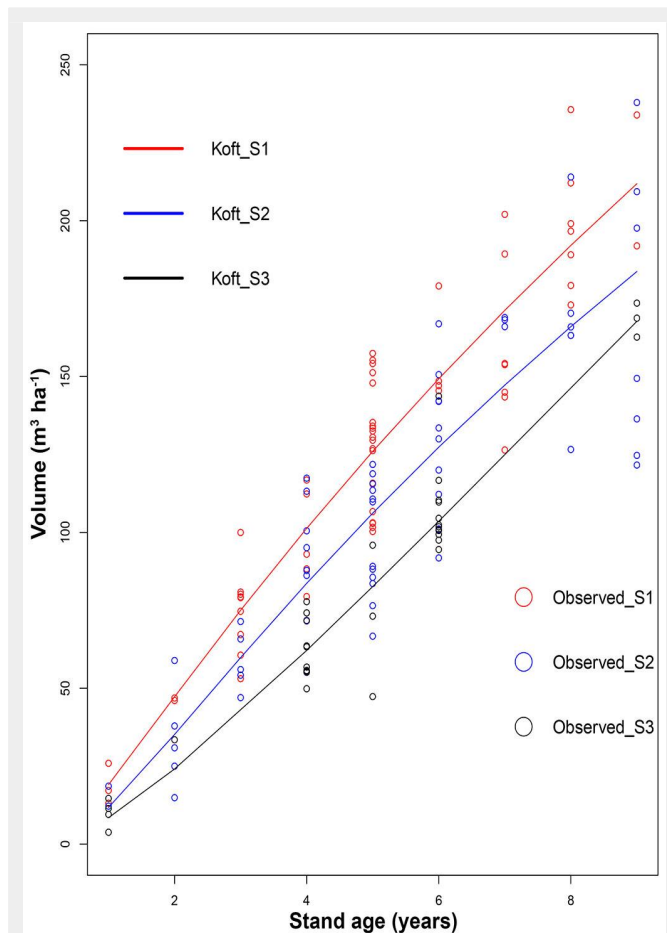


Fig. 6 - Volume growth curves of *A. mangium* for the three suitability classes by the Korf function.

tion in the study area.

**Discussion**

One of the eligible REDD+ activities concerns the enhancement of forest carbon stocks via afforestation and reforestation (<https://redd.unfccc.int/fact-sheets/unfccc->

[negotiations.html](#)). The creation of new plantations is only beneficial for climate protection if natural forests are not cleared beforehand (Heilmayr 2014). In recent years, concepts to promote the afforestation of degraded and abandoned sites have, therefore, been specifically promot-

ed (FAO 2005, Chazdon 2008). In order to achieve a variety of benefits from the plantation economy, both the locations and the tree species must be carefully selected. The present study makes a decisive contribution to this aim and is based on a transparent and straightforward approach.

Tab. 5 - Variation in volume growth of *A. mangium* by age and suitability classes as obtained by the Korf function.

| Years | S1 (Highly suitable) |                      | S2 (Moderately suitable) |                      | S3 (Marginally suitable) |                      |
|-------|----------------------|----------------------|--------------------------|----------------------|--------------------------|----------------------|
|       | V(t) (m³ ha⁻¹)       | MAI (m³ ha⁻¹ year⁻¹) | V(t) (m³ ha⁻¹)           | MAI (m³ ha⁻¹ year⁻¹) | V(t) (m³ ha⁻¹)           | MAI (m³ ha⁻¹ year⁻¹) |
| 2     | 47.3                 | 23.6                 | 35.2                     | 17.6                 | 24.1                     | 12.1                 |
| 3     | 75.0                 | 25.0                 | 59.8                     | 19.9                 | 42.4                     | 14.1                 |
| 4     | 101.3                | 25.3                 | 83.6                     | 20.9                 | 62.1                     | 15.5                 |
| 5     | 126.0                | 25.2                 | 106.2                    | 21.2                 | 82.6                     | 16.5                 |
| 6     | 149.3                | 24.9                 | 127.3                    | 21.2                 | 103.6                    | 17.3                 |
| 7     | 171.2                | 24.5                 | 147.2                    | 21.0                 | 124.8                    | 17.8                 |
| 8     | 192.1                | 24.0                 | 166.0                    | 20.7                 | 146.2                    | 18.3                 |
| 9     | 211.8                | 23.5                 | 183.7                    | 20.4                 | 167.7                    | 18.6                 |
| 10    | 230.7                | 23.1                 | 200.4                    | 20.0                 | 189.2                    | 18.9                 |
| 11    | 248.7                | 22.6                 | 216.3                    | 19.7                 | 210.7                    | 19.2                 |
| 12    | 266.0                | 22.2                 | 231.4                    | 19.3                 | 232.1                    | 19.3                 |
| 13    | 282.6                | 21.7                 | 245.9                    | 18.9                 | 253.5                    | 19.5                 |
| 14    | 298.5                | 21.3                 | 259.6                    | 18.5                 | 274.8                    | 19.6                 |
| 15    | 313.9                | 20.9                 | 272.8                    | 18.2                 | 296.0                    | 19.7                 |
| 16    | 328.7                | 20.5                 | 285.4                    | 17.8                 | 317.1                    | 19.8                 |
| 17    | 343.0                | 20.2                 | 297.6                    | 17.5                 | 338.1                    | 19.9                 |
| 18    | 356.9                | 19.8                 | 309.3                    | 17.2                 | 358.9                    | 20.0                 |

Four classes of suitability (S1 to S3 and unsuitable class) are defined and specified for the study area with regard to favourable and constraining factors (Shi et al. 2008). Subsequent to the identification of site suitability a growth model was applied to assess the potential timber production in different site classes. The yield of *A. mangium* was calculated based on a site-dependent yield model developed for *A. mangium* plantations. This allowed for assigning the productivity to each suitability class.

Self-sufficiency of raw timber for the Vietnamese economy is predicted to increase to 80% by 2020 (EU-FLEGT 2011). However, the current local wood supply is not sufficient to meet the domestic timber demand and makes the import raw material from other countries into Vietnam necessary. Based on Vietnam's development strategy for the period 2006-2020, a stable supply of raw material capable of supporting the timber-processing industry should be realized by 2020. Therefore, sustainable forest production has to be increased to satisfy the domestic timber demand by utilizing local production. In order to meet this goal, the efficiency of the forest plantations has to be increased by the selection of suitable tree species and by sustainable forest management.

Principles of sustainable forest development and land use planning often require a compromise between socio-economic development and environmental interests. Biophysical factors have a significant effect on the productivity of forest plantations, while socio-economical and economic factors have an impact on profitability and management systems. To enhance profits from forest plantations, the tree species grown need to match the specific site conditions. Good land use planning can realize higher productivity of forest land as well as decrease the area required for future timber procurement for private households and forest industries (Sedjo 1999, Ewers et al. 2009).

The stand volume yield model represents the current management practice in *A. mangium* plantations (i.e., no thinning and short rotation). The land suitability classes and volume yield provide valuable information for policymakers, planners, and stakeholders to make decisions about different forest management regimes. The yield model applied supports decisions on optimal rotation periods for sustainable production and simultaneously improves the cost-efficiency of sustainable timber production in Thai Nguyen *A. mangium* plantations. Currently, most of the *A. mangium* plantations are managed in short rotations of 5-7 years to meet the timber demand for woodchip production. Extending the length of rotation periods leads to production of assortments with higher value (e.g., sawn logs) and enhances forest carbon pools and carbon removals by timber utilization. Summarizing, the presented ap-

proach provides a valuable contribution to sustainable forest management.

The effectiveness of reforestation and FLR are strongly dependent on stakeholder needs and biophysical conditions. The suitability classification along with the growth predictions provide basic information for land use management decisions in the scope of forest landscape restoration and the implementation of plantation forestry. This basic information allows for objective allocation of afforestation while simultaneously minimizing the risk of economic losses by unsuitable site selection for afforestation activities. The extension of forest areas through afforestation and reforestation under Forest Landscape Restoration (FLR) can reduce degraded lands, increase the forest cover and boost the forest carbon stock worldwide. In addition, however, the needs of the local population must also be taken into account. Afforestation must not take place on land used for agricultural purposes. Only currently unused areas or areas with unsatisfactory tree cover should be selected for potential afforestation. Stakeholders should be involved in afforestation programmes at an early stage in order to avoid conflicts and to ensure the success of afforestation programmes.

The approach can easily be extended to other species and regions. Many restoration and reforestation efforts have partially or completely failed, mainly because tree species or provenances were planted that were not adapted to the specific local conditions (Le et al. 2014, Chazdon & Guarigueta 2018). Land suitability assessments are essential prerequisites for establishing forest plantations (Ryan et al. 2002). Site condition classification for growing study species is based on a land suitability evaluation technique developed by FAO (1984), this technique helps match ecological requirements of *A. mangium* with site conditions. Each individual environmental factor has a different effect on tree growth and forest productivity. Therefore, AHP was used to determine the weight of each factor on tree growth and forest productivity.

Taking into account site-dependent growth patterns, land suitability classifications for *A. mangium* forest plantations is combined with a site-specific growth model in order to obtain reliable information on the potential timber production. The approach of this study can be extended to other species and regions under the same environmental conditions.

## Conclusion

The study provides an approach that can guide site selection including the identification of economically unsuitable sites and facilitates the afforestation with site-adapted tree species. This safeguards the success of reforestation and FLR activities by satisfying principles such as restoring ecological function by enhancing productive land use, or meeting community livelihood

needs. The application of land suitability class evaluation and stand growth prediction as shown in the current study offer a straightforward and operational decision-making tool that supports readiness of FLR.

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## Supplementary Material

**Tab. S1** - Questionnaires for the suitability classes determination for *A. mangium* and pair wise comparison.

**Tab. S2** - Pair-wise comparisons for factors by experts and aggregation of individual judgments.

**Tab. S3** - Weights of each attribute and each factor to create a map of land suitability.

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