Soil suitability map for planted teak (*Tectona grandis* L.f.) stand growth in the mountainous area of northern Lao People's Democratic Republic

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Abstract

A soil suitability map was developed for teak (*Tectona grandis* L.f.) plantations in northern Lao People's Democratic Republic based on 110 sample sites located along a 40 km transect line running northwest–southeast in southwestern Luang Prabang Province, 63 of which included teak stands. The soils were observed to a depth of 1 m using a soil auger at 59 sites and by obtaining a soil profile at 51 sites, and the soil physicochemical properties were summarized for the 0–20 cm depth layer. In addition, the height and diameter at breast height of the teak trees and stand age were measured in a 20 × 20 m plot at each teak stand. The stand age ranged from 3 to 31 years, and the average dominant tree height ranged from 5.1 to 27.7 m. The site index (SI), which was defined as the dominant tree height at base age (20 years), was computed based on a height–growth model using the Richards function and ranged from 12.6 to 27.0. A predictive model SI based on soil physicochemical properties, site conditions, and terrain characteristics was developed using the decision tree method, which showed that CN ratio, electrical conductivity, convergence index, coarse sand fraction, slope gradient, and 22 additional factors contributed to the SI. This model was then used to construct a soil suitability map, which showed that suitable land covered approximately 50% of the study area, 8% of which was optimal land, while unsuitable land covered approximately 30% of the area.

Introduction

Nearly two-thirds of the territory of Lao People's Democratic Republic (PDR) is covered by forest. However, the majority of these land areas have been deforested and/or rapidly degraded. In particular, serious deforestation is occurring in the northern mountainous region, largely due to the expansion of shifting cultivation practices by local people living in poverty. Indigenous tree plantations are expected to mitigate the impacts of deforestation by helping to restore forest cover and providing an alternative income for local people who would otherwise depend solely on unsustainable shifting cultivation practices (MAF 2005). However, the development of sustainable and profitable tree plantations in the hilly terrain, which is characterized by high precipitation, requires that special attention be given to soil conservation measures. Therefore, the aim of this project was to propose suitable silvicultural technologies that could be used by local communities in northern Lao PDR to manage indigenous tree plantations while taking soil conservation into consideration.

Teak (*Tectona grandis* L.f.) is one of the most important tropical hardwood species in the international market for high-quality timber and is also one of the most valuable indigenous tree species for smallholder woodlots in the mountainous region of Lao PDR. Teak is native to South Asian regions that have a monsoon climate and develops on fertile soils of alluvial, limestone, and basalt origin (Kaosa-ard 1989). However, teak has also been planted across a wide variety of site conditions both within and outside its native area across the tropics, including at sites with extreme climates and soils (Kollert and Kleine 2017). Since the site/soil characteristics that are optimal for teak growth may vary according to the climate, geology, topography, etc. of a particular region, site selection is the most critical issue for the successful establishment and management of this important species (Kollert and Kleine 2017). JIRCAS and the Royal Forest Department developed a series of soil suitability maps for teak plantations in northeast Thailand. These maps were established based on soil group maps and field observations of landform and soil properties in order to describe actual soil features and limitations (Sukchan and Noda 2012). This method could be used as a basis for establishing soil suitability maps in neighboring Lao PDR. The soil suitability maps in NE Thailand were targeted toward flat and gently sloping lands because farmers were growing teak on flat land in Thailand. In contrast, teak plantations were established on sloping land in Lao PDR. For this reason, it is necessary to develop a technology adapted to sloping land. Furthermore, both countries use different soil classification systems, so we cannot directly compare the soils and soil properties.

The objective of this study was to develop a land evaluation method for teak growth in northern Lao PDR. To do this, the site index (SI), which was defined as the dominant tree height at base age, was estimated using the decision tree method, which allows taxonomic units to be subdivided into areas of similar productivities or site qualities. The resulting model was then used to establish a soil suitability map for teak plantations in northern Lao PDR based on the SI.

Materials and methods

Study sites

A transect line was established in a northwest–southeast direction from the village of Timsom in the city of Luangprabang, which is located on the Mekong River (19°48′11″ N, 101°59′54″ E), to the village of Nammok, Xiengngeun District, which is located on the mountain ridge of Phou Kham (19°31′32″ N, 102°16′20″ E) in Luangprabang Province. This transect was approximately 40 km long and approximately 300–1500 m above sea level (a.s.l.). It crossed three mountains that are divided by the Mekong and Khan rivers and their tributaries and consist of Paleozoic sedimentary rocks, limestone, and volcano-sedimentary rocks (JICA-DGEO-DOM 2008a, 2008b). The soils along the transect were primarily Acrisols and Alisols with associated Cambisols and Leptosols (NAFRI 2000).

Our study examined 110 sites along this transect, 63 of which included stands of planted teak at elevations of 287 to 1057 m a.s.l. The land uses of the remaining 47 sites were comprised of crop land and fallow forest resulting from slash-and-burn cultivation, secondary forest, and natural forest.

Tree measurement and SI assessment

A tree survey was undertaken in a 20 × 20 m plot at each teak stand site. During this survey, the diameter at breast height (DBH) was measured using a diameter tape, and the total height (H) was measured using an ultrasound distance measure (Vertex IV; Haglöf, Sweden). In addition, three sample trees were felled in each plot and the number of tree rings at ground level was counted to determine the stand age.

SI was defined as the dominant tree height at base age in each plot, which was selected as 20 years. SI was computed based on a height–growth model using the Richards function (Ishibashi et al. 2002) according to the following equations:

$$H_o = A_o \cdot \left(1\text{-}\exp(\text{-}k_o \times t)\right)^{m_o} \quad (1)$$

$$A_i = \frac{H_i}{\left(1\text{-}\exp(\text{-}k_o \times t_i)\right)^{m_o}} \quad (2)$$

$$SI_i = A_i \cdot \left(1\text{-}\exp(\text{-}k_o \times A_{SI})\right)^{m_o} \quad (3)$$

$$SI_i = H_i \cdot \left(\frac{1\text{-}\exp(\text{-}k_o \times A_{SI})}{1\text{-}\exp(\text{-}k_o \times t_i)}\right)^{m_o} \quad (4)$$

where H_o is the dominant tree height (m); t is the stand age (years); A_o, k_o, and m_o are the parameters of the guide curve; A_i, H_i, t_i, and SI_i are the parameters of the height curve, dominant tree height, stand age, and SI of the ith plot, respectively; and A_{SI} is the base age. The dominant tree height at the time of measurement (DTH) was taken as the average tree height of the 15 tallest trees in each plot. Each parameter in the Richards function for the SI curve [Equation (1)] was estimated based on the height and age of each felled tree at the time of measurement using nonlinear regression (JMP 12.0.1, SAS Inst). Although Ishibashi et al. (2010) improved the height–growth model based on the Mitscherlich function by adding more elder stand data, our study used the Richards function because the range of sample ages was similar to that of Ishibashi et al. (2002).

Soil sampling and chemical analysis

Soil samples were obtained at 20 cm depth intervals to a depth of 1 m using a soil auger at 59 sites along the transect and from each individual soil horizon in a 1 m depth soil profile at 51 sites on the slopes around the transect. At each site, the coordinate and elevation were recorded using a handheld global positioning system receiver (GPSMAP64; Garmin), and the slope aspect and gradient were measured using a clinometer.

The soil samples were air-dried and passed through a 2 mm mesh sieve, after which any visible organic fragments were manually removed before analysis. The soil pH was measured in water and in a 1 mol L^{-1} KCl suspension using a 1:2.5 w/v soil/solution ratio with the glass electrode method. Delta pH was calculated as the difference between pH(KCl) and pH(H_2O). The electrical conductivity (EC) of the soil was measured in a 1:5 soil/water ratio using the Pt electrode method. The total soil carbon (TC) and nitrogen (TN) content were determined using the dry combustion method with an NC analyzer (Sumigraph NC-220; Sumika Chemical Analysis Service, Ltd.). The particle size distribution was assessed according to the International Society of Soil Science classification (coarse sand [CoS], ≥0.2 mm; fine sand [FS], ≥0.02 mm; silt, ≥0.002 mm; and clay, <0.002 mm) using the pipette method after dispersion and oxidation of the organic matter (van Reeuwijk 2002).

The cation exchange capacity (CEC) and exchangeable calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) were extracted using a 1.0 M ammonium acetate solution adjusted to pH 7.0, while exchangeable aluminum (ex.Al) was extracted with 1 M KCl. The concentrations of these cations were then determined using an inductively coupled plasma emission spectrometer (ICPE-9000; Shimadzu Inc.). The total base cations (TBC) was calculated as the sum of exchangeable Ca, Mg, K, and Na, and the effective CEC (ECEC) was calculated as the sum of TBC and ex.Al. Base saturation (BS) and effective base saturation (EBS) were then calculated as TBC divided by CEC and ECEC, respectively. In addition, CEC_{clay} was calculated based on the CEC and clay content. Available phosphorus (P) was determined according to the Bray 2 method, while the P concentration was determined using the ascorbic acid-molybdenum blue method. Finally, the bulk density (BD) and fine earth density (<2 mm) of the soil profile were measured using the core method (Soil Survey Laboratory 1996).

The concentration/value of each soil physicochemical property at a depth of 0–20 cm in the soil profile was calculated from the integrated mass of each material in each soil horizon.

Spatial prediction of soil suitability based on SI

The spatial prediction covered the area of the city of Luangprabang and Xiengngeun District (coordinate range: 19.35–20.03° N, 101.80–102.60° E).

Terrain analyses of the topographic wetness index (TWI), topographic position index (TPI), terrain ruggedness, curvatures, channel networks, slope position and heights, and landforms were performed using the NASA Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) with a spatial resolution of 30 m in SAGA 5.0.0 (Conrad et al. 2015). The spatial diversity of each soil physicochemical property at a depth of 0–20 cm was predicted by the decision tree method in Python 3.7 using Scikit-learn v.0.21.3 (Pedoregosa et al. 2011) based on soil cross-section surveys, physicochemical analyses, topographical data, and the survey area, which was divided into the three mountains in the study area. The model for prediction of SI was established based on the analysis of the actual tree census data responsibility to variables of field-observed soil and terrain features using decision tree classification. A soil suitability map for teak plantations was then produced based on the predicted SI model, which incorporated the predicted soil and terrain spatial diversities.

Results and discussion

Tree census and SI of teak plantations

The age of the teak stands in the 63 plots ranged from 3 to 31 years, with nearly all of these stands having been established between 1995 and 1999 (41%) or 2006 and 2010 (43%). The

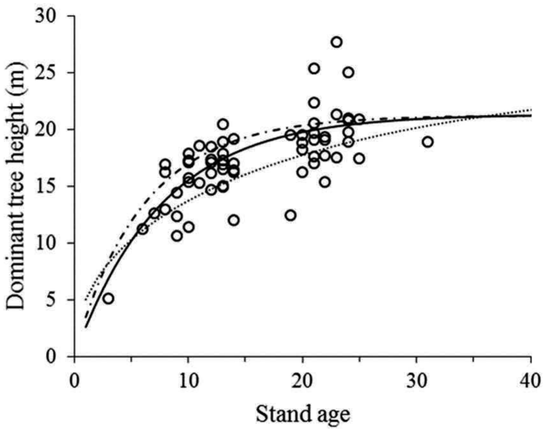

Fig. 1. Dominant tree height curve for teak (*Tectona grandis*) stands in northern Lao People's Democratic Republic estimated using the Richards function (solid line) and raw data (open circles). The chain line and dotted line represent dominant tree height curves that were constructed using the parameters estimated by Dieters et al. (2014) and Ishibashi et al. (2002), respectively.

average number of trees in the plots was 1113 ± 357 trees per hectare (mean ± SD) (range = 425 to 2128). The average DBH was 16.0 ± 3.4 cm (range = 6.0 to 25.1 cm), the average H was 15.0 ± 3.1 m (range = 6.3 to 23.5 m), and the average DTH was 17.3 ± 3.6 m (range = 5.1 to 27.7 m).

The estimated guide curve is shown in Figure 1. The parameters A_o, k_o, and m_o were estimated as 21.33, 0.131, and 1.009 (RMSE = 2.911), respectively, while the mean estimated SI for the plots was 19.3 ± 2.8 (range = 12.6 to 27.0). Using the census of young teak trees (5–16 years) in smallholder woodlots in Luangprabang Province (Dieters et al. 2014), the parameters A_o, k_o, and m_o were estimated as 21.28, 0.155, and 0.934 (RMSE = 2.238), respectively, with a mean SI of 20.4 ± 2.7 (range = 14.6 to 25.9). By contrast, in a study in northeast Thailand, Ishibashi et al. (2002) estimated the parameters A_o, k_o, and m_o as 25.59, 0.030, and 0.465 (RMSE = 2.925), respectively. Since the parameter A_o represents the upper limit of tree height growth, k_o represents the response to time (i.e., the initial growth rate), and m_o represents the shape form of the SI curve (Teraoka 1995), the study sites had a lower A_o value as compared to northeast Thailand, despite their initial height growth being faster (Figure 1). By contrast, the initial height growth of trees at the study sites was slightly slower than that of young teak trees in Luangprabang, but their upper limits of height growth were similar. These differences in the shape of the SI curves can be explained by the fact that the stand studied by Ishibashi et al. (2002) was 5–48 years of age, making it wider and older than the stands in our study sites. This suggests that ranges of sample age are needed for alignment when comparing the growth model to the other study. In Lao PDR, observation of older teak stands is needed for improvement of the height–growth model.

Table 1. Soil physicochemical properties in the 0–20 cm depth layer at the study sites (n = 110).

				Mechanical composition				pH			
	TC	TN	CN ratio	CoS	FS	Silt	Clay	H_2O	KCl	EC	Available P
	g kg^{-1}			%						mS m^{-1}	P_2O_5 mg kg^{-1}
Mean	26.6	2.6	9.8	11.9	14.0	27.5	41.6	6.0	4.7	4.6	9.5
Standard deviation	31.8	2.9	1.8	8.1	6.7	7.2	11.9	0.7	0.8	5.6	21.5
Median	20.8	2.2	9.7	10.1	12.5	27.4	40.8	6.0	4.6	3.2	3.1
Upper 95% confidence interval	32.6	3.2	10.2	13.4	15.3	28.9	43.9	6.1	4.8	5.6	13.5
Lower 95% confidence interval	20.6	2.1	9.5	10.4	12.8	26.1	39.4	5.8	4.5	3.5	5.4

	Exchangeable										
	Ca	Mg	K	Na	Al	TBC	ECEC	CEC	BS	EBS	CEC_{clay}
	cmolc kg^{-1} soil								%		cmolc kg^{-1} clay
Mean	14.6	3.1	0.34	0.04	0.67	18.1	18.8	19.8	75.0	86.6	27.8
Standard deviation	34.1	3.2	0.26	0.06	1.18	35.2	35.0	13.4	57.3	24.0	30.0
Median	6.1	2.4	0.28	0.02	0.24	10.3	10.6	16.4	67.9	98.9	22.3
Upper 95% confidence interval	21.1	3.8	0.39	0.06	0.89	24.8	25.4	22.3	85.8	91.1	33.5
Lower 95% confidence interval	8.2	2.5	0.29	0.03	0.45	11.5	12.2	17.2	64.2	82.1	22.1

TC: total carbon; TN: total nitrogen; CN ratio: carbon-nitrogen ratio; CoS: coarse sand; FS: fine sand; KCl: potassium chloride; EC: electrical conductivity; Available P: available phosphorus; Ca: calcium; Mg: magnesium; K: potassium; Na: sodium; Al: aluminum; TBC: total base cations; ECEC: effective cation exchange capacity; CEC: cation exchange capacity; BS: base saturation; EBS: effective base saturation; CECclay: cation exchange capacity per clay

Soil physicochemical properties in the 0–20 cm depth layer

Table 1 shows the average soil physicochemical properties in the 0–20 cm depth layer across the 110 study sites. Half of the study sites had poor soil humus (TC < 20 g kg^{-1}), and nearly all of the sites contained soils that had clayey textures, were slightly acidic, and had a moderate CEC and a high BS and EBS.

A comparison of soil characteristics associated with high teak productivity in Brazil (Kollert and Kleine 2017) showed that the percentages of study sites that had optimum and unsuitable soil characteristics were 64% and 11% for Ca, 4% and 15% for Al, 36% and 0% for organic matter content, 45% and 5% for clay content, and 37% and 25% for Mg, respectively. Thus, soils with unsuitable physicochemical properties for teak growth appear to have a limited distribution in the study area, with the exception of Mg limitation.

Soil suitability map for teak plantation growth

A total of 66 factors associated with site and terrain characteristics (plan curvature, profile curvature, convergence index, TWI, LS-factor, channel network base level, channel network distance, valley depth and relative slope position in the basic analysis, curvature classification, geomorphons, clusters, landforms based on Iwahashi and Pike, convexity, terrain surface texture, TPI-based landforms (100 to 1000 m, 200 to 3000 m, and 500 to 5000 m), convergence index, convergence index (search radius), gradient (downslope distance), gradient difference, mass balance index, multi-scale TPI (maximum scale: 8 or 27), surface area, slope height, valley depth, normalized height, standardized height, mid-slope position, general curvature, profile curvature, plan curvature, tangential curvature, longitudinal curvature, cross-sectional curvature, minimal curvature, maximal curvature, total curvature, flow line curvature, terrain ruggedness index (1 cell, 10 cell), TPI (0 to 100 m, 0 to 500 m, 0 to 2000 m), local curvature, upslope curvature, local upslope curvature, downslope curvature, local downslope curvature, vector terrain ruggedness (VRM; 1 cell, 5 cell, 10 cell), positive openness, negative openness, flow accumulation, specific catchment area, flow path length, slope length, flow direction, altitude, slope gradient, slope aspect, geological area) and 33 factors associated with soil physicochemical properties [pH(H_2O), pH(KCl), delta pH, EC, TC, TN, CN ratio, CEC, ex.Ca, ex.Mg, ex.K, ex.Na, TBC, BS, ex.Al, ECEC, EBS, CoS, FS, silt, clay, CECclay, P_2O_5, Ca saturation, Mg saturation, Ca/Mg ratio, Ca+Mg, Ca+Mg saturation, Al saturation, Ca/Al ratio, fine earth density, BD, and thickness of A horizon] were used to predict SI values for the 63 sites containing teak plantations using a decision tree analysis with 10-fold cross validation by hyperparameter tuning with the GridSearchCV module. The model with the best estimated parameters divided the observed teak sites into 35 units according to the following 27 factors: CN ratio, EC, convergence index, CoS, slope gradient, profile curvature, channel network distance, terrain surface texture, pH(KCl), pH(H_2O), CECclay, geomorphons, normalized height, local upslope curvature, gradient difference, fine earth density, landforms based on Iwahashi and Pike, ex.Na, slope length, VRM using 10cell, slope height, specific catchment area, TPI-based landforms, plan curvature, clay content, BS, and delta pH (tree maximum depth = 8, R^2 = 0.508, generalization performance: 53.6%). Among these, the CN ratio, EC, convergence index, CoS, and slope gradient contributed approximately 9.1, 9.0, 6.7, 6.4 and 6.0%, respectively, to the model. The sites with the highest SI values (over 22.2) had 1) a high conversion index (>−0.178), medium CN ratio (9.7 to 11.4), short channel network distance (≤68.3), low CoS (≤31.1%), high pH(KCl) (>4.3), high fine earth density (>0.84 kgm^{-3}), and a low BS (≤50%); 2) a low convergence index (≤−0.178), high EC (>2.4), large slope gradient (>9.2%), low pH(H_2O) (<6.4), low CoS (≤15.7%), low ex.Na (≤0.014 $cmol_ckg^{-1}$), and a low VRM (≤0.099); and 3) a low convergence index (≤−0.178), high EC (>2.4), small slope gradient (≤9.2%), and a low CECclay (≤43.7 $cmol_ckg^{-1}$). The percentages of samples and precision of these three leaves were 1.1, 4.9, and 9.3%, and 75, 72, and 82%, respectively. By contrast, the sites with the lowest SI values (under 15.2) had 1) a high conversion index (>−0.178), high CN ratio (>11.4), and a rough terrain surface texture (>18.8); 2) a high conversion index (>−0.178), low CN ratio (<11.4), long channel network distance (>68.3), and a long slope length (>43.5); 3) a high conversion index (>−0.178), low CN ratio (<11.4), short channel network distance (<68.3), low CoS (<31.1%), high pH(KCl) (>4.3), and a low fine earth density (<0.84 kgm^{-3}); and 4) a low convergence index (≤−0.178), high EC (>2.4), large slope gradient (>9.2%), high pH(H_2O) (>6.4), and a large gradient difference (<−0.035). The percentage of samples and precisions of these four leaves were 4.9, 1.9, 1.6, and 1.9% and 89, 43, 50, and 57%, respectively.

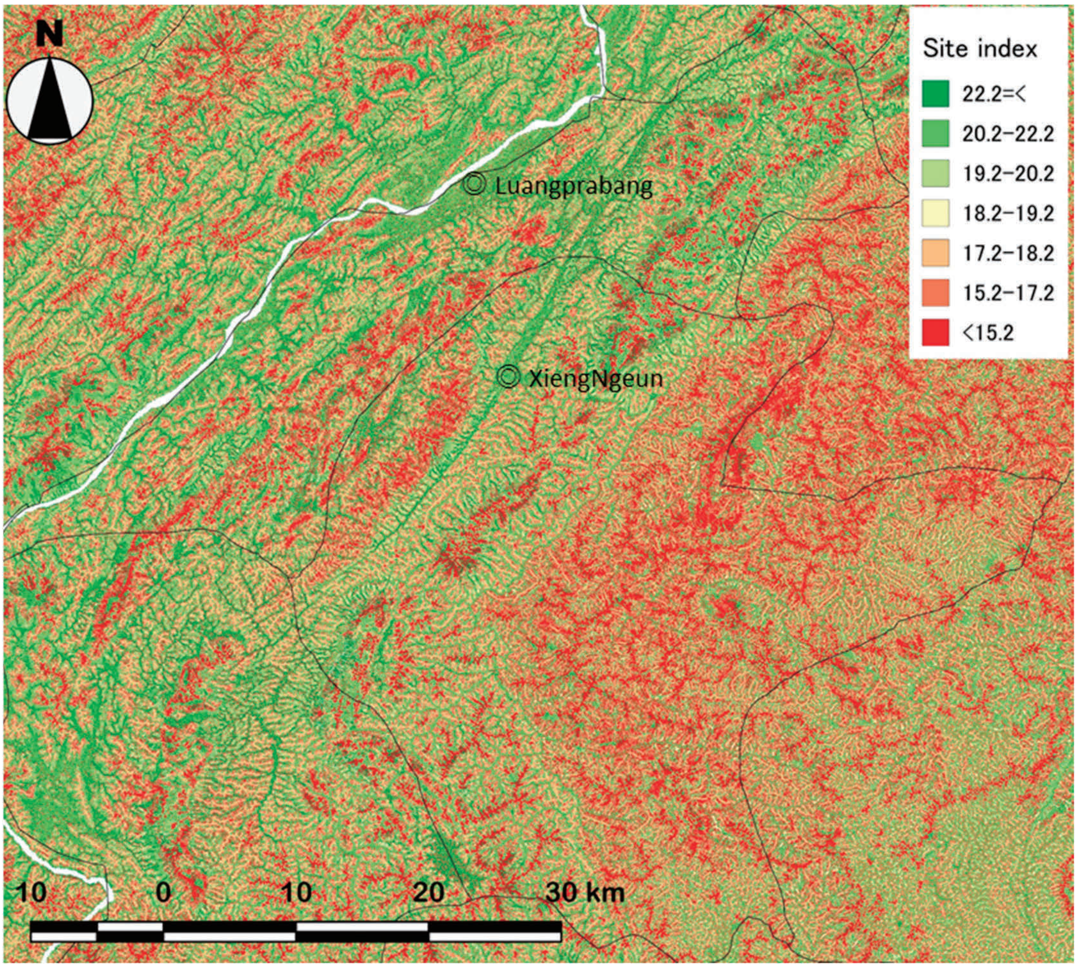

Fig. 2. Soil suitability map for teak plantations in the city of Luangprabang and Xiengngeun District, Luangprabang Province.

Table 2. Coverage of each site index range in the predicted area

Site index	<15.2	15.2–17.2	17.2–18.2	18.2–19.2	19.2–20.2	20.2–22.2	> 22.2
km^2	1266.12	389.23	1028	185.27	831.88	1644.09	435.32
%	21.9	6.7	17.8	3.2	14.4	28.4	7.5

A soil suitability map was developed for teak plantations in the study area by applying the results of the above decision tree analysis to the spatially predicted soil physicochemical properties (CN ratio, EC, CoS, pH(H_2O), pH(KCl), CECclay, ex.Na, clay content, BS, and ΔpH), the results of the terrain analysis (convergence index, profile curvature, channel network distance, terrain surface texture, geomorphons, normalized height, local upslope curvature, gradient difference, landforms, slope length, VRM, slope height, specific catchment area, and plan curvature), and the geomorphological characteristics (slope gradient) using GIS (Figure 2). This showed that approximately one-third of the study area had a low SI (<17.2), and only 8% of the study area had a high SI (≥22.2) (Table 2). A large area of flat land around the river basin had a higher SI value, with various parts having low SI values. By contrast, the SI value changed rapidly over short distances on the sloping lands of the mountain area, following the complicated topography. These findings suggest that teak growers must be careful to select appropriate land even within a small area when establishing teak plantations.

It should be noted that this soil suitability map did not consider the effects of surface geology as a parent material for the soil, as the study area was divided into only three areas along the mountain range. In the study area, limestone forms outstanding karst topography. During the field survey, limestone was seen to form the upper part of the mountain range that is located near the Mekong River and next to the southeast mountain range, but some of the limestone that occurs on the slopes of these mountains is mixed with other kinds of rocks, such as sandstone. In general, soils that are derived from limestone have unique characteristics, such as large amounts of Ca, small amounts of Al, high BS levels, high pH, and clayey textures (Imaya et al. 2005). Consequently, the soil physicochemical properties on the mountain slopes in the study area might be controlled by the contamination ratio of soil materials derived from limestone and other parent materials. Therefore, the prediction accuracy of soil that is suitable for teak growth could be improved in the future by clarifying the relationship between soil physicochemical properties and the ratio of contaminated limestone-origin materials. Moreover, another study should be conducted to validate the predicted soil suitability map.

Conclusion

A soil suitability map for establishing teak plantations in a part of southwestern Luangprabang Province was constructed based on soil cross-section surveys, soil physicochemical analyses, tree census plots, and topographical analyses. This map indicates that the average height of dominant trees was 20 years old, which is the age at which planted teak is harvested in Luangprabang. Thus, use of this map will allow suitable sites to be selected for establishing teak plantations, improving productivity, and reducing the risk of plantation failure or poor growth.

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References

Conrad O, Bechtel B, Bock M, Dietrich H, Fischer E, Gerlitz L, Wehberg J, Wichmann V, Boehner J (2015) System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geosci Model Dev 8, 1991-2007. doi:10.5194/gmd-8-1991-2015

Dieters M, Newby J, Cramb R, Sexton G, McNamara S, Johnson M, Vongphacsouvanh S (2014) Final report: Enhancing on-farm incomes through improved silvicultural management of teak in Luang Prabang Province of Lao PDR. Australian Centre for International Agricultural Research, Canberra

Imaya A, Ohta S, Tanaka N, Inagaki Y (2005) General chemical properties of brown forest soils developed from different parent materials in the submontane zone of the Kanto and Chubu Districts, Japan. Soil Sci Plant Nutr 51:873–884

Ishibashi S, Ishida H, Okabayashi M, Sirilak S, Wanussakul R, Klaikaew N, Intuman C, Cha-umpol C (2002) Yield prediction table on *Tectona grandis* (Teak) in Northeast Thailand. (Study Report) 11th July 2002. The Reforestation and Extension in the Northeast of Thailand Phase II (REX II)

Ishibashi S, Sakai M, Noda I, Vacharangkura T, Krongkitsiri V, Kamolpanit D, Himmapan W (2010) Yield Prediction Table on Tectona grandis (Teak) in Northeast Thailand (Revised edition). RFD-JIRCAS Joint Research Project, Bangkok

Japan International Cooperation Agency, Department of Geology, Ministry of Energy and Mines, Department of Mines, Ministry of Energy and Mines (2008a) Explanatory notes for the geological and mineral resources map of Lao People's Democratic Republic, 1:1,000,000: the geological mapping and mineral information service project for promotion of mining industry in the Lao PDR (2006-2008). JICA, Tokyo

Japan International Cooperation Agency, Department of Geology, Ministry of Energy and Mines, Department of Mines, Ministry of Energy and Mines (2008b) Geological and mineral resources map of Lao People's Democratic Republic, 1:1,000,000. JICA, Tokyo

Kaosa-ard A (1989) Teak (*Tectona grandis* Linn. f), its natural distribution and related factors. Nat His Bull Siam Soc 29:55–74

Kollert W, Kleine M (2017) The global teak study. Analysis, evaluation and future potential of teak resources. IUFRO World Series Volume 36. Vienne

Ministry of Agriculture and Forestry (2005) Forestry strategy to the year 2020 of the Lao PDR. 89pp.

NAFRI (2000) Soil Map of Lao PDR. Ministry of Agriculture and Forestry (MAF), National Agriculture and Forestry Research Institute (NAFRI), Soil Survey and Land Classification Center (SSLCC), Vientiane

Pedregosa F, Varoquaux G, Gramfort A, Michel V, Thirion B, Grisel O, Blondel M, Prettenhofer P, Weiss R, Dubourg V, Vanderplas J, Passos A, Cournapeau D, Brucher M, Perrot M, Duchesnay E (2011) Scikit-learn: Machine Learning in Python. J Machine Learning Res 12:2825–2830

Soil Survey Laboratory (1996) Bulk density cores field moist (4A3a). In: Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42 ver. 3.0. Natural Resources Conservation Service, US Department of Agriculture, Washington DC. pp.137–138

Sukchan S and Noda I (2012) Improvement of soil suitability mapping for teak plantations in Northeast Thailand. JIRCAS Working Report No.74:27–32

Teraoka Y (1995) The development of polymorphic site index curves: using a varying shape form parameter model. Bull Kyushu Univ Forest 72:135–142 (in Japanese)

Van Reeuwijk LP (2002) Procedures for Soil Analysis sixth edition. Technical paper 9, International Soil Reference and Information Centre, Wageningen