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Effects of Topography, Soil Organic Matter, and Chemical Properties on the Growth of Teak (*Tectona grandis*) Plantations in Northeast Thailand

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Abstract

Information about site conditions is essential to select teak (*Tectona grandis*) plantation sites in Northeast Thailand. We examined the effects of topography (slope steepness, elevation, and slope aspect), soil organic matter, and chemical factors on tree growth (site index) in 7- to 30-year-old teak plantations (n = 87) in Northeast Thailand. Soil organic matter and chemistry data were collected from the topsoil (0 cm-20 cm) and subsoil (40 cm-60 cm). The linear mixed model indicated that teak growth was positively affected by slope steepness ($P < 0.05$) and Ca content and negatively by Na content. Mg showed a weak correlation ($P < 0.1$) due to its association with Ca. We suggest that slope steepness alters the balance of exchangeable cations, and that accumulation of soil organic matter due to surface drainage plays an important role. In conclusion, suitable sites for growing teak in the study area in Northeast Thailand are those on slopes with topsoil rich in Ca.

Discipline: Forestry
Additional key words: Acrisol, farm forestry, site conditions, site index, site selection

Introduction

Teak (*Tectona grandis*) is one of the most valuable timber species harvested in the tropics (Kaosa-ard 1989, Tewari 1992). Teak is grown in many parts of Asia, Africa, and the tropical Americas for multiple agroforestry purposes (Pandey & Brown 2000, Midgley et al. 2007, Roshetko et al. 2013). An economic profitability study of the reforestation methods typically used in Northeast Thailand, Niskanen (1998) showed that planting teak for timber is more profitable compared with planting eucalyptus for agroforestry (intercropping). However, high productivity comes from good and easily accessible sites (Enters 2000). Furthermore, the yields and economic returns of teak plantations depend greatly on the site quality (Kaosa-ard 1998, Balagopalan & Rugmini 2008, Noda & Himmapan 2014). Site quality maps with corresponding yield tables are crucial. They must be created to select planting sites and management of plantations because teak growth is sensitive to edaphic factors, particularly soil fertility, and has a wide range of growth rates depending on soil characteristics (Tanaka et al. 1998). The expansion of forest plantations in Northeast Thailand should be supported by detailed information on the potential for teak growth in a given area, and the positive and negative impacts that plantations could have in those locations (Mahannop 2004, Noda & Himmapan 2014).

Teak plantations in Northeast Thailand have various site conditions regarding soil properties and topography. Few studies have examined the effects of topographic factors, such as slope steepness and aspect, on teak growth, or have related these factors to soil chemistry in Thailand. Therefore, studies evaluating the effects of site conditions on the growth of teak plantations in the region are essential for the selection of suitable sites for teak

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plantation. Teak grows best in deep, well-drained alluvial soils derived from limestone, schist, gneiss, shale, and certain volcanic rocks, such as basalt (Kaosa-ard 1989, Pandey & Brown 2000). In dry, sandy, or acidic soil (pH < 6.0), teak grows quite poorly and develops misshapen stems (Kulkarni 1951, Kaosa-ard 1989, Srisuksai 1991). Studies have indicated that teak requires relatively large amounts of Ca for growth and development and that the level of Ca in the soil is an indicator of site quality (Kaul et al. 1979, Kaosa-ard 1989). Moreover, soil pH limits the distribution and development of teak (Kaosa-ard 1989). The ideal range of acidity for teak growth and quality is pH 6.5-7.5 (Kaosa-ard 1989, Tewari 1992, Tanaka et al. 1998). In Northeast Thailand, the low growth rate of teak seedlings planted in Acrisols may be due to low pH, low nutrient content, and low water-holding capacity of the soil (Kayama et al. 2016). Therefore, correcting the high acidity and poor fertility through fertilization may improve the growth rate of teak in Acrisols (Abod & Siddiqui 2002; Wichiennopparat et al. 2012; Zhou et al. 2012, 2017).

Regarding topographic factors that affect teak growth, teak prefers the hotter southern and western aspects in areas with very heavy rainfall in India (Seth & Yadav 1959). Site index (SI) is a species-specific measure of the actual or potential forest productivity and indicates site quality (Helms 1998). When Watanabe et al. (2010) evaluated the influence of soil physicochemical properties and other site conditions on teak growth in Ghana, they found the slope, gradient (slope steepness), slope aspect, drainage, and soil pH were unrelated to the SI. Instead, they found that rich soil with high organic matter (OM) content, which increases water-holding capacity and provides N and exchangeable Ca and Mg, led to enhanced growth. In northern Thailand, Sakurai et al. (2002) analyzed the SI of teak plantations using a multiple regression method with soil properties and the topographic factor of slope steepness. The study showed that the SI was represented by slope steepness and pH at 20 cm depth among 45 variables representing soil properties in layers of 0 cm-5 cm and 20 cm-25 cm soil depth and related properties. Previous studies have revealed that soil properties and topography are important factors affecting teak growth; however, those studies were conducted in areas with soil conditions relatively well suited to teak trees. The soil conditions of the Korat Plateau in Northeast Thailand, the target area of the present study, generally include poor drainage and low nutrition. The influencing factors of teak growth in this area remain unclear.

In this study, we investigated the effects of site conditions on the growth of teak plantations in Northeast Thailand. Topographic factors and soil properties were used as representative site conditions. Then, we determined how these site conditions might affect teak growth and how such data could support selecting the sites for teak plantations in Northeast Thailand.

Materials and methods

1. Study sites

This study was conducted on teak plantations in Loei, Nong Bua Lam Phu, and Udon Thani Provinces (17°-18°N, 101°-103°20′E), located in the northern part of the northeastern region of Thailand (Fig. 1). Farmers living in the study area are interested in growing teak and have experience managing teak plantations (Himmapan et al. 2010, Furuya et al. 2012). Two-thirds of the region is covered with the alluvial plateau of the Korat basin at an elevation of 100 m-300 m, and mountain ranges surround the region to the south, west, and northeast (Wongwiwatchai & Paisancharoen 2001). The climate of this area has two major seasons: the southwest monsoon, a wet season with a maximum monthly rainfall of ~300 mm, and the northeast monsoon, characterized by mostly dry weather with occasional light showers. Annual rainfall ranges from 1,100 to 1,800 mm, and monthly mean temperature ranges from 22°C to 29°C (Phien et al. 1980). The undulating plateau accounts for ~80% of Northeast Thailand, the basement rocks consist of sandstone or siltstone of the Mesozoic age underlain by rock salt bed, and the sediments covering the land surface are deposits formed by the mass movement of the weathered mantle of the bedrock (Mitsuchi et al. 1989). The soils in the study area are classified as Acrisols (FAO 2014) and are characterized as shallow with lateritic gravelly clay, low fertility, and well or moderately draining (LDD 2005).

Sites were selected based on plantation age and site conditions using registration lists of private teak plantations at the Royal Forest Department regional office and forest management history at the state-owned Forest Industry Organization (FIO). We examined 87 sites at teak plantations (Loei [n = 51], Nong Bua Lam Phu [n = 24], and Udon Thani [n = 12] Provinces), including 20 sites—Lof1 to Lof20—belonging to the FIO in Loei Province (Fig. 1, Table 1). The 67 teak plantations that do not belong to the FIO were planted and managed by farmers. While investigating plantation ownership, land use before teak planting was identified as maize or cassava cultivation (n = 34), grassland or bare land (30), tamarind or other fruit cultivation (6), secondary forest (6), teak plantation (4), paddy field (2), and unclear (5). Chemical fertilization was conducted

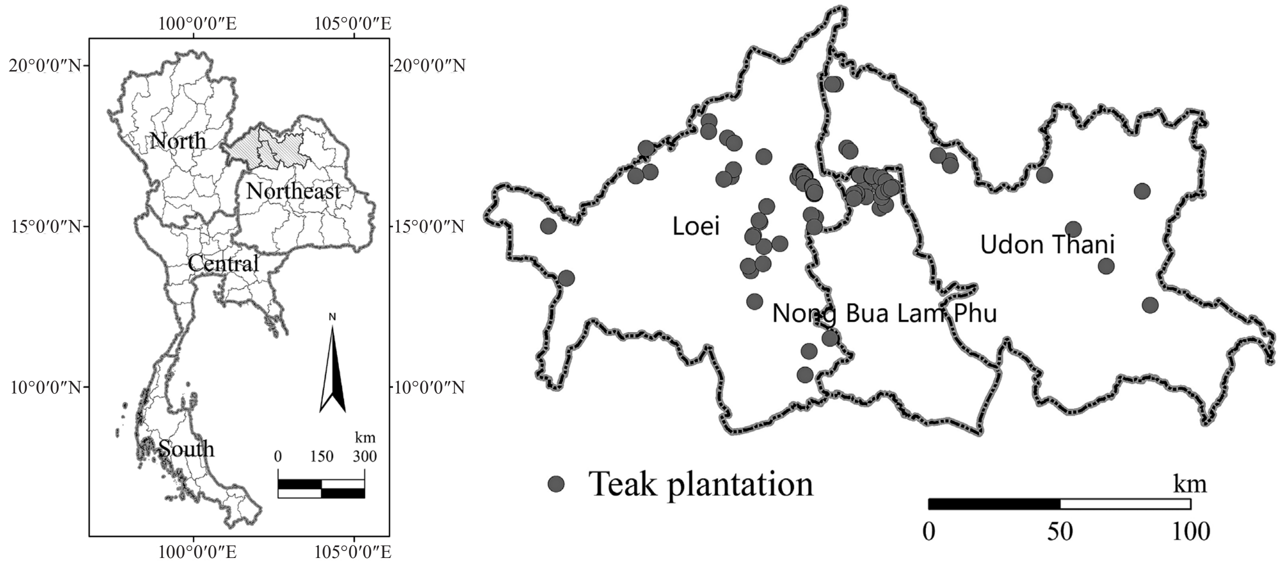

Fig. 1. Location of teak study plantations in Northeast Thailand

after teak planting at 26 sites, but the fertilizer compositions were unknown. Only teak was planted at 82 sites, whereas five FIO sites had the growth of maize between teak trees in the first few years after teak planting. Thus, previous land use and teak tree fertilization, both factors likely to affect teak growth, were based on the owner's memory. This study excluded these historical traits of sites from analysis and instead focused on current site conditions of topography and soil properties.

2. Field survey and soil chemical analysis

Field surveys were conducted to obtain data on the teak growth rate, topographic factors, and soil properties. At each 40 × 40-m plot, we measured tree diameter at breast height (DBH) using a diameter tape; tree height using a Vertex IV ultrasound distance measurer (Haglöf Inc., Långsele, Sweden); and the topographic factors of slope steepness, elevation, and slope aspect using an electronic clinometer (EC II; Haglöf), GPSMap62sc (Garmin Ltd., Olathe, KS, USA), and a compass glass (HB-3; Shakujii Keiki Co. Ltd.), respectively. We estimated the SI using the following formula from Vacharangkura (2012):

$$SI = DTH_t \cdot \left[\frac{31.755015621\{1-0.772111113 \exp(-0.27606608 \times 30)\}}{31.755015621\{1-0.772111113 \exp(-0.27606608 \times t)\}} \right]$$

where DTH_t is the dominant tree height (in meters) at stand age t. This SI curve is based on the height growth rates of teak trees in plantations in Northeast Thailand and uses a reference age of 30 y, which is commonly used for teak in Thailand. Stand age was calculated from the planting year. DTH is generally defined as the mean height of the tallest 40-100 trees per hectare of stand age (West 2009). The 16 tallest trees on each 0.16-ha plot were used to estimate DTH in this study.

Three replicates of topsoil (0 cm-20 cm) and subsoil (40 cm-60 cm) were collected and pooled into composite samples by soil depth class in each plot. Soil samples were air-dried before analysis of their chemical composition. Soil pH was evaluated according to the method of Peech (1965) in a soil slurry in distilled water (1:1) using a pH meter (SevenCompact pH/Ion S220; Mettler Toledo, Columbus, OH, USA). Electrical conductivity (EC) was evaluated using an EC meter (SevenCompact Conductivity S230; Mettler Toledo) with a soil:water (1:5) mixture. Soil organic matter (SOM) was estimated using the Walkley–Black method (Walkley & Black 1934). Total N was determined using the Kjeldahl method. Available P was measured using the Bray-2 method with a spectrophotometer (Y530; Jasco, Oklahoma City, OK, USA). Exchangeable base cations (Ca, Mg, K, and Na) were extracted using a soil-NH_4OAc solution of 1:10 (Jones 2001), and their concentrations were determined via colorimetry using a flame spectrophotometer (PinAAcle 900F; PerkinElmer, Waltham, MA, USA). After replacing the exchangeable base cations, cation exchange capacity (CEC) was determined via ammonia distillation (Chapman 1965), washing with ethanol, and replacing 10% KCl. Base saturation (BS) was calculated as the proportion of the sum of the exchangeable base cations (Ca, Mg, K, and Na) to CEC.

3. Data analysis

All analyses were conducted using R version 4.0.0 statistical software. Each analyzed plot (n = 87) had the following attributes: SI, topographic factors (slope steepness, elevation, and aspect), and soil properties (SOM, soil pH, total N, available P, exchangeable base cations [Ca, Mg, K, and Na], CEC, EC, and BS). The soil properties dataset had subsets for topsoil and subsoil. Total N had missing data due to instrument problems at our laboratory; therefore, we imputed the missing data with a random forest method using the missForest package (Stekhoven & Bühlmann 2012). This imputation resulted in a normalized root mean square error of 0.004902. The available P; exchangeable Ca, Mg, K, and Na; CEC; and EC values showed skewed distributions. We applied a logarithmic transformation to the data for analysis according to the recommendations of Dahl et al. (1961) & Watanabe et al. (2010).

Pairwise relationships between topographic factors or soil properties and SI were examined using Pearson's correlation coefficients (r), whereas one-way analysis of variance (ANOVA) was conducted to compare the effect of aspect on SI. The properties of each soil depth class were used to examine the pairwise relationships of SI.

The joint influence of topographic factors and soil properties on teak growth was examined using the SI value as a response variable in a linear mixed model (LMM). As predictors, we used slope steepness, soil properties with correlations to SI, and a random effect of site, and then we constructed a correlation matrix of soil properties in advance to remove multicollinearity. A backward selection procedure was performed using the step function (Kuznetsova et al. 2017) to eliminate the least significant variable until we had significant components at the 5% level in the model. LMM fitting was conducted using the significant variables as predictors with a random site effect to examine the effect on SI. We assumed a normal error distribution and identity link function and applied the maximum likelihood method to the LMM, and marginal R^2 was calculated to identify the proportion of the variance explained by fixed effects using the r2_nakagawa function (Nakagawa et al. 2017).

Results

1. Stand growth, topographic factors, and soil properties

Stand age ranged from 7 y to 30 y (18.3 y ± 4.9 y [mean ± standard deviation]; Table 1). Stand mean DBH ranged from 7.9 cm to 37.4 cm (15.3 cm ± 5.9 cm). Stand mean height ranged from 8.3 m to 25.1 m (14.7 m ± 3.4 m), and DTH ranged from 11.4 m to 26.5 m (17.5 m ± 3.3 m). The SI values of plantations ranged from 13.6 to 32.2 (22.0 ± 3.7). Although we observed variations in the age and size of the studied stands, wood density, which has a strong effect on growth, does not vary widely in Thailand, including the study area (Kenzo et al. 2020).

The studied teak plantations were generally in mid-slope positions with low slope steepness (3.5° ± 3.6°). The most common slope aspect was south (n = 16), followed by north, east, southwest, west, northeast, northwest, and southeast. Pairwise relationships between topographic factors and the SI are shown in Figure 2, and an outlier in the west slopes was detected in the boxplot because of fertilizing effect on SI. Slope was weakly and positively correlated with SI (r = 0.164, P = 0.13). Elevation did not correlate significantly with SI (r = −0.041, P = 0.71). There was no significant difference between SI and slope aspect (ANOVA, P = 0.91).

Table 2 shows soil properties at different soil depths. Soil pH was acidic and became slightly more acidic with depth ($P < 0.001$). SOM and total N ($P < 0.001$), as well as exchangeable Ca and K ($P < 0.05$), were more concentrated in the topsoil compared with in the subsoil. EC and BS values were higher in the topsoil than in the subsoil ($P < 0.001$), whereas available P, exchangeable Mg and Na, CEC, and EC did not differ with soil depth at the 5% level. Table 3 shows pairwise relationships between soil properties and SI. SOM, total N, exchangeable Ca, and BS had significant positive correlations with SI, whereas exchangeable Na showed significant negative correlations in both soil depth classes. Exchangeable Mg and CEC had significant positive correlations in the topsoil, whereas exchangeable K had a significant negative correlation in the subsoil. Soil pH showed a weak positive correlation for the topsoil (P = 0.10). Available P and EC did not correlate with SI for either soil class. Figure 3 shows the relationships between soil properties and SI in the topsoil.

2. Linear mixed model analysis

To examine the joint influence of topographic factors and soil properties on teak growth, we constructed a LMM for backward selection using the SI as a response variable. We selected the following predictor variables regarding their pairwise relationships with SI: slope, soil properties (OM, pH, and exchangeable cations [Ca, Mg, K, and Na]), and BS in the topsoil (0 cm-20 cm). Because teak roots are confined to the upper 20 cm-30 cm of the soil (Ngampongsai 1973, Singh & Srivastava 1985, Sakurai et al. 2002), we focused on the topsoil properties. Moreover, we removed total N and CEC due to their strong correlations with OM and exchangeable Mg,

Table 1. Plantation age and growth information at study sites

Plot	Age (y)	Mean DBH (cm)	Mean H (m)	DTH (m)	SI	Plot	Age (y)	Mean DBH (cm)	Mean H (m)	DTH (m)	SI
Plantations in Loei Province						Lof14	22	17.4 ± 4.6	14.6 ± 1.7	16.6 ± 0.3	19.0
Lo1	12	7.9 ± 2.4	9.3 ± 2.5	12.8 ± 0.6	19.1	Lof15	30	29.0 ± 5.5	19.6 ± 2.7	19.9 ± 0.9	19.9
Lo2	16	17.6 ± 5.3	17.6 ± 4.7	24.1 ± 0.8	31.7	Lof16	30	24.9 ± 5.0	17.9 ± 1.8	19.4 ± 0.8	19.4
Lo3	17	12.1 ± 5.4	12.1 ± 4.4	16.2 ± 0.4	20.7	Lof17	30	29.1 ± 5.2	20.7 ± 1.7	21.8 ± 0.8	21.8
Lo4	18	25.3 ± 5.2	20.9 ± 2.2	22.3 ± 0.5	27.8	Lof18	9	13.2 ± 2.6	11.0 ± 1.8	12.7 ± 0.6	21.2
Lo5	10	14.2 ± 5.2	15.5 ± 4.2	20.1 ± 0.8	32.2	Lof19	9	12.6 ± 2.8	10.8 ± 1.8	12.9 ± 0.7	21.5
Lo6	16	12.8 ± 3.3	14.4 ± 3.0	18.2 ± 0.6	23.9	Lof20	30	30.8 ± 6.3	21.5 ± 2.9	22.3 ± 1.1	22.3
Lo7	17	16.3 ± 2.7	17.5 ± 1.3	19.4 ± 0.3	24.9	**Plantations in Nong Bua Lam Phu Province**					
Lo8	18	13.8 ± 3.4	17.2 ± 2.3	20.5 ± 0.4	25.6	Nob1	13	9.9 ± 2.9	11.5 ± 2.4	15.6 ± 0.6	22.4
Lo9	17	14.5 ± 3.9	15.2 ± 2.7	19.3 ± 0.5	24.7	Nob2	16	15.2 ± 4.3	16.1 ± 2.8	19.6 ± 0.5	25.8
Lo10	17	16.0 ± 3.6	17.9 ± 2.9	21.4 ± 0.4	27.4	Nob3	16	15.9 ± 3.0	15.8 ± 1.1	17.3 ± 0.4	22.7
Lo11	17	14.3 ± 2.6	15.3 ± 1.6	17.3 ± 0.3	22.1	Nob4	16	10.5 ± 2.9	11.6 ± 2.1	15.1 ± 0.6	19.9
Lo12	17	15.3 ± 3.6	15.9 ± 2.4	18.6 ± 0.5	23.9	Nob5	16	10.0 ± 2.8	11.5 ± 2.3	15.1 ± 0.3	19.8
Lo13	18	13.5 ± 3.4	14.8 ± 3.0	18.4 ± 0.9	23.0	Nob6	16	10.5 ± 3.5	12.5 ± 3.2	17.6 ± 0.8	23.2
Lo14	17	10.8 ± 2.6	10.6 ± 1.6	13.0 ± 0.8	16.6	Nob7	16	10.1 ± 3.4	10.9 ± 3.1	17.5 ± 1.2	23.0
Lo15	17	12.2 ± 2.9	13.2 ± 2.0	16.2 ± 0.4	20.7	Nob8	16	12.7 ± 4.9	15.1 ± 4.4	22.2 ± 1.4	29.2
Lo16	18	15.3 ± 4.0	14.5 ± 2.9	16.0 ± 0.3	19.9	Nob9	17	17.9 ± 5.8	16.9 ± 5.0	20.2 ± 0.5	25.9
Lo17	16	13.3 ± 2.8	13.7 ± 2.0	16.2 ± 0.5	21.3	Nob10	17	10.6 ± 2.7	12.6 ± 2.4	16.2 ± 0.3	20.7
Lo18	18	14.2 ± 2.6	15.1 ± 1.8	17.2 ± 0.2	21.5	Nob11	18	12.1 ± 3.3	13.4 ± 2.3	17.0 ± 0.8	21.3
Lo19	18	12.5 ± 3.5	13.7 ± 2.2	16.4 ± 0.4	20.5	Nob12	16	11.4 ± 3.1	11.9 ± 2.1	14.9 ± 0.4	19.6
Lo20	17	8.8 ± 3.0	9.2 ± 1.6	11.4 ± 0.3	14.5	Nob13	16	10.0 ± 3.3	9.8 ± 2.6	13.9 ± 0.9	18.3
Lo21	18	15.0 ± 3.9	16.1 ± 3.1	18.7 ± 0.3	23.4	Nob14	16	11.4 ± 2.9	12.7 ± 1.7	14.9 ± 0.3	19.7
Lo22	19	15.7 ± 2.6	16.4 ± 1.3	18.0 ± 0.3	21.9	Nob15	15	15.6 ± 3.5	17.1 ± 3.2	21.8 ± 0.8	29.5
Lo23	16	9.2 ± 2.0	10.9 ± 1.5	12.9 ± 0.3	17.0	Nob16	18	11.7 ± 3.5	13.8 ± 2.7	17.9 ± 0.9	22.3
Lo24	19	12.7 ± 3.3	14.7 ± 2.5	18.4 ± 0.4	22.4	Nob17	17	12.5 ± 1.9	14.3 ± 1.2	15.9 ± 0.3	20.4
Lo25	19	11.0 ± 3.8	11.0 ± 1.9	13.2 ± 0.4	16.1	Nob18	17	12.4 ± 3.1	14.7 ± 2.8	18.8 ± 0.9	24.1
Lo26	19	15.3 ± 3.7	14.3 ± 1.8	16.5 ± 0.4	20.1	Nob19	18	9.0 ± 2.5	10.8 ± 2.0	14.1 ± 0.3	17.7
Lo27	16	11.3 ± 3.2	11.7 ± 1.8	14.2 ± 0.6	18.7	Nob20	18	14.2 ± 2.9	16.7 ± 2.2	19.2 ± 0.5	24.0
Lo28	19	13.1 ± 2.9	13.8 ± 1.4	15.3 ± 0.2	18.7	Nob21	18	18.0 ± 3.9	17.9 ± 2.6	20.0 ± 0.2	25.0
Lo29	19	13.4 ± 2.9	15.4 ± 2.2	18.1 ± 0.3	22.1	Nob22	17	11.7 ± 2.8	12.6 ± 2.0	15.4 ± 0.6	19.7
Lo30	21	13.5 ± 4.0	16.7 ± 3.0	21.3 ± 0.5	24.8	Nob23	14	9.4 ± 2.8	8.8 ± 2.1	11.8 ± 0.7	16.4
Lo31	15	10.5 ± 2.4	10.2 ± 1.9	12.3 ± 0.3	16.6	Nob24	15	10.9 ± 2.7	13.4 ± 2.0	16.1 ± 0.3	21.8
Lof1	29	37.4 ± 7.7	25.1 ± 2.5	25.7 ± 1.3	26.1	**Plantations in Udon Thani Province**					
Lof2	7	14.9 ± 3.3	12.5 ± 2.7	15.4 ± 0.7	28.1	Ud1	20	16.2 ± 6.8	16.3 ± 4.3	21.7 ± 0.9	25.9
Lof3	29	33.6 ± 4.8	21.8 ± 1.7	22.3 ± 0.7	22.6	Ud2	22	14.6 ± 3.9	16.1 ± 2.4	18.9 ± 0.2	21.6
Lof4	25	22.0 ± 4.3	16.9 ± 1.7	18.2 ± 0.7	19.7	Ud3	20	14.5 ± 3.8	15.5 ± 3.0	19.3 ± 0.2	23.1
Lof5	20	16.4 ± 4.3	14.9 ± 1.8	17.1 ± 0.7	20.4	Ud4	20	12.2 ± 3.6	14.8 ± 3.1	20.2 ± 1.0	24.1
Lof6	28	23.3 ± 2.9	17.4 ± 0.9	18.0 ± 0.7	18.5	Ud5	20	11.8 ± 3.2	11.9 ± 2.3	14.8 ± 0.4	17.7
Lof7	28	24.9 ± 2.5	17.5 ± 1.2	18.1 ± 0.3	18.6	Ud6	20	9.6 ± 2.2	8.3 ± 2.3	12.5 ± 1.3	14.9
Lof8	19	15.4 ± 2.7	15.0 ± 1.5	17.1 ± 0.5	20.9	Ud7	20	9.9 ± 2.6	8.5 ± 2.5	11.4 ± 0.5	13.6
Lof9	19	16.1 ± 2.9	17.0 ± 2.1	20.0 ± 0.5	24.5	Ud8	20	13.7 ± 3.4	13.8 ± 2.4	16.7 ± 0.6	20.0
Lof10	7	11.4 ± 3.0	9.5 ± 1.9	12.1 ± 0.4	22.0	Ud9	22	22.0 ± 8.6	20.6 ± 5.5	26.5 ± 0.8	30.3
Lof11	7	12.2 ± 2.4	10.0 ± 1.3	11.4 ± 0.3	20.8	Ud10	19	17.1 ± 4.9	17.2 ± 3.0	20.9 ± 0.7	25.5
Lof12	26	28.2 ± 3.0	21.3 ± 1.4	22.2 ± 0.7	23.5	Ud11	20	16.8 ± 4.7	18.4 ± 3.2	22.5 ± 0.5	26.8
Lof13	24	27.2 ± 5.3	18.7 ± 2.7	18.8 ± 0.7	20.7	Ud12	19	13.8 ± 3.9	13.9 ± 2.7	17.2 ± 0.5	21.0

DBH, diameter at breast height; H, tree height; DTH, dominant tree height; SI, site index. Mean ± SD

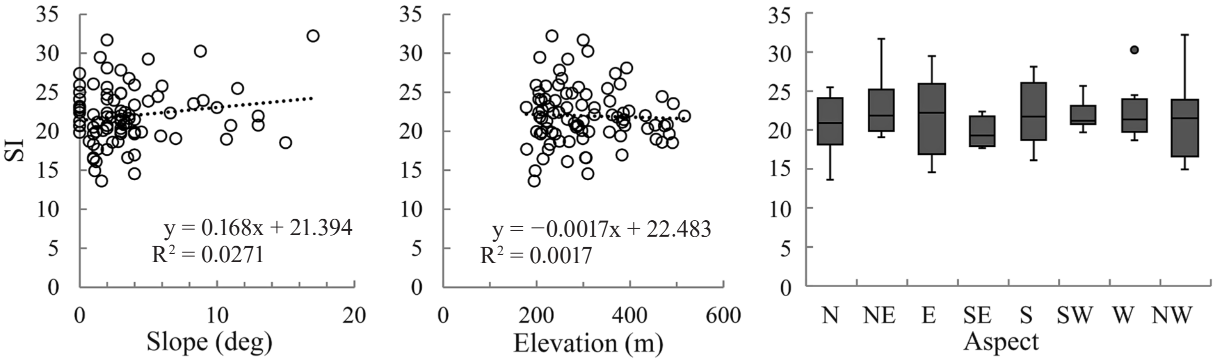

Fig. 2. Pairwise relationships of topographic factors to the SI variable

Table 2. Mean of soil properties by soil depth class

Depth (cm)	OM ($g\ kg^{-1}$)	pH	Total N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Exch. Ca ($cmolc\ kg^{-1}$)	Exch. Mg ($cmolc\ kg^{-1}$)
0-20	22.63 ± 10.83	5.87 ± 0.47	1.23 ± 0.47	5.38 ± 9.75	4.81 ± 4.03	1.35 ± 0.65
	(4.04-61.70)	(5.00-7.34)	(0.32-3.10)	(0.28-61.15)	(0.54-31.51)	(0.24-3.86)
40-60	10.87 ± 5.84	5.46 ± 0.59	0.57 ± 0.27	4.03 ± 12.57	3.58 ± 3.68	1.39 ± 0.69
	(0.34-35.41)	(4.50-7.70)	(0.02-1.77)	(0.03-105.00)	(0.44-28.87)	(0.26-4.20)

Depth (cm)	Exch. K ($cmolc\ kg^{-1}$)	Exch. Na ($cmolc\ kg^{-1}$)	CEC ($cmolc\ kg^{-1}$)	EC ($mS\ m^{-1}$)	BS (%)
0-20	0.25 ± 0.18	0.08 ± 0.05	12.31 ± 6.40	4.17 ± 3.38	52.80 ± 17.80
	(0.01-0.81)	(0.01-0.18)	(1.47-42.80)	(1.00-18.00)	(14.20-101.00)
40-60	0.20 ± 0.16	0.10 ± 0.06	12.78 ± 6.43	2.55 ± 2.30	42.75 ± 16.28
	(0.01-0.89)	(0.02-0.35)	(1.51-34.60)	(0.40-20.00)	(12.84-89.96)

n = 87. Mean ± SD. Numbers in parentheses are minimum and maximum.

Table 3. Correlation between soil properties and site index

Depth	OM	pH	Total N	Available P	Exch. Ca	Exch. Mg
0-20 cm	0.328 **	0.176 ns	0.306 **	0.032 ns	0.485 ***	0.301 **
40-60 cm	0.267 *	0.040 ns	0.275 *	−0.053 ns	0.380 ***	0.207 ns

Depth	Exch. K	Exch. Na	CEC	EC	BS
0-20 cm	−0.124 ns	−0.301 **	0.277 **	0.012 ns	0.231 *
40-60 cm	−0.219 *	−0.282 *	0.173 ns	0.059 ns	0.295 **

n = 87. Logarithmic transformation is applied for available P, exchangeable cations (Ca, Mg, K, Na), CEC, and EC.
***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; ns, no significance

respectively (Table 4). Backward stepwise regression of the LMM indicated that exchangeable Ca and Na and slope steepness were significant factors for SI. In contrast, exchangeable Mg ($F = 3.81$, $P = 0.054$) was not selected at the 5% level (Table 5). Based on LMM fitting using the three significant variables, the proportion of the total variance explained by the fixed effects remained at 31.3%, but we found that teak growth was explained by the concentrations of exchangeable Ca (positively, $P < 0.001$) and Na (negatively, $P < 0.05$) in the topsoil, and by slope steepness (positively, $P < 0.05$) in this study (Table 6).

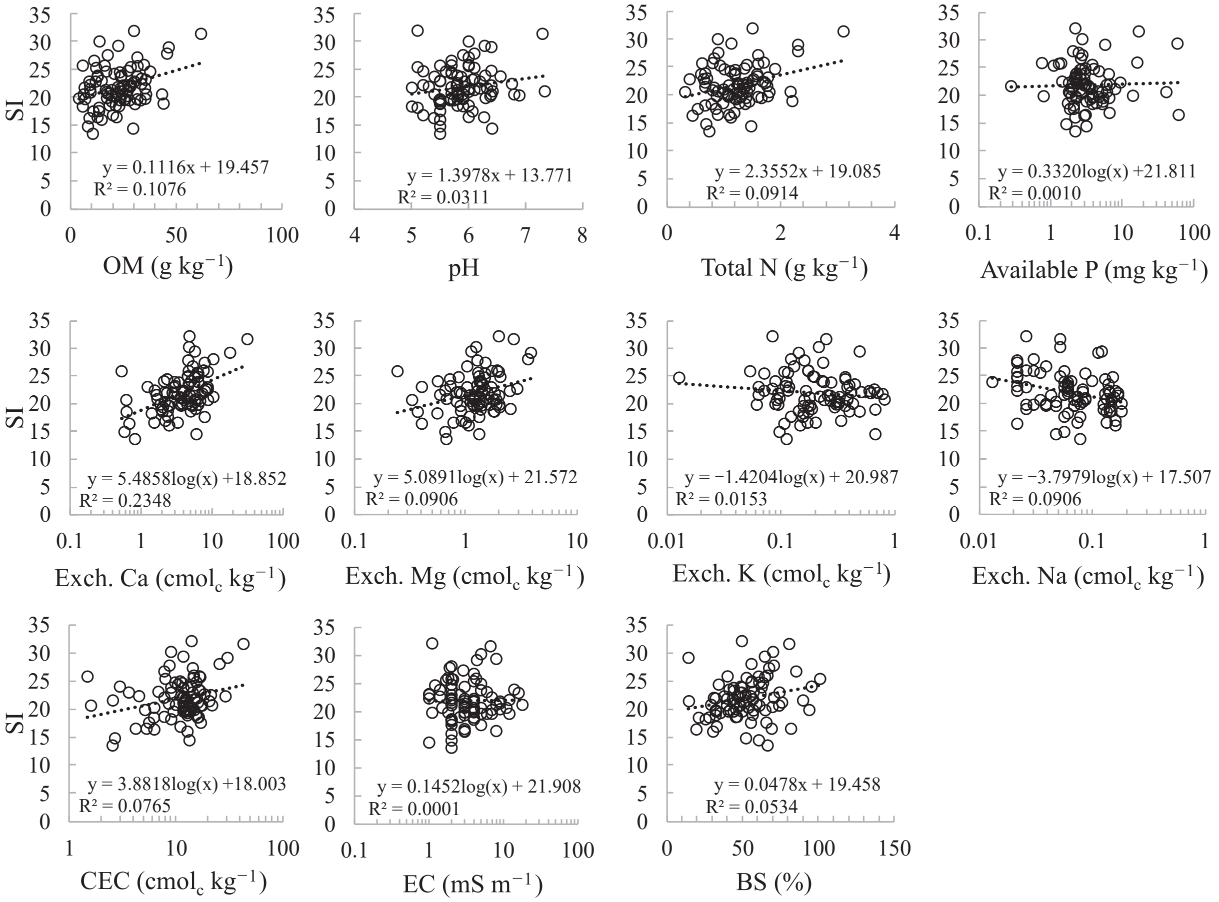

Fig. 3. Pairwise relationships of topsoil properties to the SI variable

Table 4. Correlation matrix of soil properties of the depth 0 cm-20 cm

	pH	Total N	Available P	Exch. Ca	Exch. Mg	Exch. K	Exch. Na	CEC	EC	BS
OM	0.359 ***	0.949 ***	0.147 ns	0.680 ***	0.607 ***	0.221 *	−0.168 ns	0.689 ***	0.232 *	−0.092 ns
pH		0.340 **	0.154 ns	0.552 ***	0.281 **	0.262 *	0.148 ns	0.323 **	0.577 ***	0.327 **
Total N			0.109 ns	0.663 ***	0.676 ***	0.264 *	−0.040 ns	0.713 ***	0.216 *	−0.117 ns
Available P				−0.016 ns	−0.146 ns	0.157 ns	0.162 ns	−0.059 ns	0.240 *	0.057 ns
Exch. Ca					0.788 ***	0.093 ns	−0.202 ns	0.798 ***	0.234 *	0.228 *
Exch. Mg						0.185 ns	−0.086 ns	0.833 ***	0.056 ns	−0.067 ns
Exch. K							0.557 ***	0.385 ***	0.462 ***	−0.374 ***
Exch. Na								0.046 ns	0.256 *	−0.368 ***
CEC									0.217 *	−0.342 **
EC										0.029 ns

n = 87. Logarithmic transformation is applied for available P, exchangeable cations (Ca, Mg, K, Na), CEC, and EC.
****P* < 0.001; ***P* < 0.01; **P* < 0.05; ns, no significance

Discussion

1. Effects of topographic factors

The analyses in the present study suggest that elevation and slope aspects do not affect teak growth in the study area, whereas slope steepness positively affects it. The small elevation range (~300 m in the study area) may have weakened the relationship between elevation and teak growth. Our results showed that slope steepness was significantly important, with a positive effect on teak

Table 5. Results of backward selection for site index as response variables in linear mixed model

Response variable		Predictor variables							
		Slope	OM	pH	Exch. Ca	Exch. Mg	Exch. K	Exch. Na	BS
SI	*F*	4.20 *	0.41 ns	0.19 ns	23.40 ***	3.81 ns	0.70 ns	6.54 *	0.24 ns
	P	0.043	0.523	0.668	<0.001	0.054	0.406	0.012	0.627

n = 87. Soil properties are from 0 cm-20 cm depth. Logarithmic transformation is applied for exchangeable Ca, Mg, K and Na.
F: *F*-value; ****P* < 0.001; **P* < 0.05; ns, no significance

Table 6. Fitting summary of the best linear mixed model for site index as response variables

Response variable	Predictor variables	Estimate	Std. error	df	*t*-value	*P*-value	AIC	R^2
SI	Exch. Ca	4.915	1.030	87	4.77	<0.001 ***	452.5	0.313
	Exch. Na	−2.954	1.155	87	−2.56	0.012 *		
	Slope	0.188	0.092	87	2.05	0.044 *		
	(Intercept)	15.040	1.472	87	10.22	<0.001 ***		

n = 87. Soil properties are from 0 cm-20 cm depth. Logarithmic transformation is applied for exchangeable Ca and Na. R^2: marginal R-square; *t*-value: Satterthwaite's method
****P* < 0.001; **P* < 0.05

growth at the 5% level, as was exchangeable Ca concentration.

In teak plantations in the savanna woodlands of West Africa, there was no significant correlation between SI and slope steepness or elevation. Soil N nutrition, rooting depth, and precipitation were the most important variables influencing teak growth (Drechsel & Zech 1994). Watanabe et al. (2010) reported that teak SI was not impacted by site factors, including steepness, aspect, slope position, or drainage in teak plantations, in Ghana. In contrast, our results concur with the results of the study on the growth of teak plantations in northern Thailand by Sakurai et al. (2002), who showed that slope steepness was positively related to SI. Moreover, our results confirm their field observation that increased surface drainage and more OM in the surface soil layer on sloping land improve teak growth. However, teak growth is depressed on precipitous slopes, which have shallow and poor soil, and teak trees grow best in mid-slope positions, where the soils have higher levels of nutrients than those of the hilltop or bottomland soils (Seth & Yadav 1959, Zech & Drechsel 1991). Our results cover relatively lower slope conditions in mid-slope positions, suggesting that slope topography affects teak growth. As Sakurai et al. (2002) reported, sloping land has better surface drainage and greater accumulation of SOM, which may allow the topsoil to retain more exchangeable Ca, rather than exchangeable Mg and K, in this study area.

2. Effects of soil properties

Teak requires a relatively large amount of Ca for its growth and development (Kaul et al. 1979). Our results reveal that higher exchangeable Ca concentrations are critical to teak growth, and exchangeable Na is negatively associated with growth (Table 6). The negative effect of exchangeable Na is likely related to increasing saturation of Ca cations, as Na showed low contribution (< 1%) to CEC.

SOM improves the physical conditions of soil (Sommerfeldt 1984, Wehr et al. 2017) and contributes to the increased water-holding capacity and water content of the soil, supporting teak growth (Watanabe et al. 2010). Soil total N is an important factor affecting the growth of many tropical trees, including teak (Drechsel & Zech 1994, Watanabe et al. 2010, Zhou et al. 2012, Hattori et al. 2013), as N is primarily used for the leaf photosynthetic apparatus, and thus contributes to carbon assimilation ability (Evans 1989, Kenzo et al. 2016, 2019). SOM was strongly correlated with soil total N (Table 4) at our study sites, and both significantly correlated with SI (Table 3). However, OM was not selected as a significant factor influencing teak growth in LMM analysis (Table 5). Because exchangeable Ca had a significant positive correlation with OM in topsoil, we speculate that SOM supports the effect of Ca on SI.

Kaosa-ard (1989) suggested that soil pH limits the distribution and stand development of teak and that the optimal pH range for growth and quality is 6.5-7.5. Topsoil pH (5.0-7.3) slightly correlated with SI, whereas subsoil pH (4.5-7.7), which was outside the optimal pH range noted by Kaosa-ard (1989) at some sites, did not correlate with SI (Table 3). Topsoil pH showed a significant positive correlation with exchangeable Ca, and weak but significant positive correlations with OM, total N, and exchangeable Mg were also observed in the topsoil (Table 4). We speculate that the effect of Ca is strong, followed by those of OM, total N, and Mg, on the soil of the study area.

In this study, we focused on the current soil organic and chemical properties. Soil moisture also affects teak growth (Watanabe et al. 2010). Thus, soil physical properties, such as water content and water-holding capacity, could be additional important factors that explain teak growth in the study area. The history of land use and fertilization was not considered but may also affect teak growth or soil properties at some sites. Some of the variance in SI that remains unexplained by the LMM is likely explained by soil physical properties and management history.

Conclusions

In the present study, we investigated the effects of topography, SOM, and chemical properties at two depth ranges on SI for the growth of teak plantations. We concluded that exchangeable Ca content in topsoil was a critical factor affecting teak growth, followed by Mg. Slope topography positively affected teak growth, whereas elevation and slope aspects were not associated with growth. We conclude that suitable site conditions for teak plantations in this study area in Northeast Thailand occur on slopes with topsoil rich in Ca and OM. Further research is warranted to investigate the effects of physical properties of soil and management history on teak growth in the area.

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Appendix Table. Dataset used in this study

Plot	Age	DBH (cm)	H (m)	DTH (m)	SI	Slope (deg)	Elevation (m)	Aspect	Soil depth 0 cm-20 cm OM ($g\ kg^{-1}$)	pH	Total N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Exch. Ca ($cmolc\ kg^{-1}$)	Exch. Mg ($cmolc\ kg^{-1}$)	Exch. K ($cmolc\ kg^{-1}$)	Exch. Na ($cmolc\ kg^{-1}$)	CEC ($cmolc\ kg^{-1}$)	EC ($mS\ m^{-1}$)	BS (%)	Soil depth 40 cm-60 cm OM ($g\ kg^{-1}$)	pH	Total N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Exch. Ca ($cmolc\ kg^{-1}$)	Exch. Mg ($cmolc\ kg^{-1}$)	Exch. K ($cmolc\ kg^{-1}$)	Exch. Na ($cmolc\ kg^{-1}$)	CEC ($cmolc\ kg^{-1}$)	EC ($mS\ m^{-1}$)	BS (%)
Lo1	12	7.90	9.31	12.82	19.07	7	299	NE	44.00	5.50	2.20	3.15	5.92	2.53	0.19	0.03	15.33	2.60	56.53	8.10	4.80	0.40	1.30	2.53	2.80	0.10	0.05	18.41	0.70	29.80
Lo2	16	17.60	17.60	24.08	31.69	2	300	NE	61.70	7.30	3.10	17.05	31.51	2.71	0.25	0.05	42.80	6.70	80.64	18.70	7.70	0.90	1.65	28.87	2.05	0.14	0.08	34.61	5.20	89.96
Lo3	17	12.14	12.14	16.17	20.72	0	389	NA	35.70	5.40	1.80	1.80	8.78	1.79	0.09	0.03	17.54	1.50	61.04	17.80	4.90	0.90	1.50	6.23	1.77	0.06	0.05	19.71	0.60	41.15
Lo4	18	25.34	20.91	22.27	27.83	3	249	S	17.60	5.90	0.90	2.45	4.63	1.27	0.16	0.02	8.63	1.90	70.60	14.10	5.30	0.70	1.50	3.05	1.51	0.13	0.03	9.24	1.50	51.04
Lo5	10	14.20	15.51	20.13	32.21	17	233	NW	30.00	5.10	1.50	2.20	4.82	1.98	0.08	0.03	13.95	1.10	49.53	9.70	4.80	0.50	1.25	2.56	1.42	0.07	0.04	12.01	0.60	34.00
Lo6	16	12.82	14.40	18.19	23.94	9	240	E	12.90	5.40	0.60	2.25	2.97	1.39	0.11	0.01	9.01	1.40	49.73	14.60	4.90	0.70	1.35	1.82	1.09	0.10	0.02	8.22	0.60	36.82
Lo7	17	16.25	17.50	19.41	24.88	3	276	N	37.70	5.20	1.90	4.00	6.39	2.05	0.20	0.02	15.46	2.00	56.01	20.90	4.50	1.10	1.55	3.48	1.51	0.11	0.02	18.38	0.80	27.87
Lo8	18	13.75	17.22	20.52	25.65	2	290	SW	28.40	5.10	1.40	3.80	6.21	1.29	0.12	0.03	14.57	1.70	52.54	16.20	4.80	0.80	1.55	5.91	1.34	0.11	0.04	17.72	0.80	41.76
Lo9	17	14.45	15.22	19.29	24.72	2	306	E	23.30	5.70	1.20	2.55	5.71	1.49	0.01	0.02	11.42	1.20	63.32	13.70	5.20	0.70	2.00	4.22	1.65	0.07	0.11	11.55	0.70	52.44
Lo10	17	15.96	17.92	21.39	27.41	0	369	NA	31.60	6.00	1.60	2.75	7.92	1.50	0.24	0.02	14.36	2.90	67.43	11.60	5.10	0.60	2.55	5.91	1.29	0.12	0.02	12.47	1.80	58.88
Lo11	17	14.33	15.30	17.26	22.12	1	324	SW	25.13	5.93	1.26	3.10	3.99	0.88	0.51	0.08	7.72	12.00	70.71	11.59	6.13	0.58	2.45	3.48	1.02	0.27	0.07	6.98	3.00	69.33
Lo12	17	15.27	15.87	18.62	23.86	5	357	NW	23.80	5.87	1.19	2.60	3.42	1.36	0.28	0.06	11.64	5.00	44.03	5.43	5.14	0.27	1.45	1.98	1.42	0.53	0.09	12.86	4.00	31.27
Lo13	18	13.48	14.84	18.42	23.02	0	324	NA	30.30	5.93	1.52	2.65	2.89	1.03	0.38	0.06	8.94	2.00	48.74	35.41	5.59	1.77	1.95	4.48	1.31	0.32	0.08	14.82	4.00	41.73
Lo14	17	10.75	10.59	12.95	16.60	1	306	NW	21.76	6.27	1.09	61.15	3.29	0.78	0.17	0.07	5.27	8.00	81.82	2.76	6.46	0.14	16.50	1.15	0.32	0.07	0.03	2.33	2.00	67.05
Lo15	17	12.18	13.24	16.17	20.72	2	287	SW	6.36	5.82	0.32	41.35	0.62	0.33	0.16	0.07	1.59	4.00	74.14	3.80	5.82	0.19	22.45	0.44	0.37	0.16	0.07	2.08	3.00	49.88
Lo16	18	15.32	14.53	15.96	19.95	3	312	S	35.41	5.69	1.77	1.95	4.48	1.31	0.32	0.08	14.82	4.00	41.73	19.60	5.07	0.98	1.10	2.73	1.29	0.18	0.07	15.80	2.00	26.99
Lo17	16	13.33	13.71	16.17	21.28	0	300	NA	27.01	7.34	1.35	7.95	10.46	1.34	0.33	0.07	16.05	18.00	76.01	16.06	5.30	0.80	1.65	5.45	1.35	0.21	0.07	15.31	4.00	46.32
Lo18	18	14.21	15.12	17.22	21.52	3	266	S	16.63	6.10	0.83	3.50	4.92	1.09	0.26	0.04	12.13	9.00	52.00	16.22	5.13	0.81	1.75	4.06	1.06	0.21	0.06	11.88	2.00	45.43
Lo19	18	12.50	13.70	16.41	20.51	1	285	N	19.51	6.89	0.98	1.85	6.83	1.11	0.27	0.07	11.88	9.00	69.68	15.01	5.09	0.75	1.40	5.31	1.25	0.26	0.13	15.07	4.00	46.15
Lo20	17	8.79	9.16	11.35	14.55	4	310	E	29.68	6.41	1.48	3.15	6.05	1.32	0.68	0.05	13.35	1.00	60.62	10.87	6.14	0.54	1.40	4.06	1.39	0.64	0.13	14.33	3.00	43.41
Lo21	18	14.98	16.11	18.70	23.37	4	297	NE	35.43	6.07	1.77	2.25	5.68	1.27	0.40	0.06	16.78	16.00	44.15	12.39	5.85	0.62	2.80	4.75	1.37	0.21	0.09	12.62	5.00	50.89
Lo22	19	15.70	16.36	17.98	21.94	13	517	S	6.75	5.00	1.08	2.95	2.31	1.82	0.61	0.17	12.32	3.00	39.89	14.45	5.50	0.60	2.05	2.20	1.48	0.43	0.15	9.16	3.00	46.51
Lo23	16	9.16	10.88	12.89	16.96	4	383	E	20.02	5.20	1.12	6.65	2.20	0.92	0.34	0.16	11.00	3.00	32.91	6.77	4.70	0.50	2.33	1.88	1.01	0.39	0.16	15.00	2.00	22.99
Lo24	19	12.68	14.66	18.37	22.42	3	248	S	9.27	5.80	0.78	9.40	1.57	0.65	0.12	0.14	4.49	2.00	55.21	6.87	5.70	0.24	8.18	1.65	0.78	0.10	0.15	5.38	2.00	49.88
Lo25	19	11.04	11.04	13.20	16.11	1	266	S	14.74	5.50	1.14	2.20	2.50	1.06	0.15	0.16	12.74	2.00	30.41	5.09	4.80	0.59	0.95	4.20	1.73	0.29	0.35	25.09	2.00	26.18
Lo26	19	15.25	14.33	16.45	20.08	2	297	W	17.24	6.30	1.09	14.10	3.81	1.30	0.43	0.18	12.57	4.00	45.59	9.89	6.30	0.51	3.78	5.07	1.72	0.68	0.14	11.83	4.00	64.25
Lo27	16	11.33	11.74	14.18	18.66	3	270	W	21.34	5.80	1.22	1.73	5.03	1.78	0.40	0.18	16.30	2.00	45.40	9.76	5.60	0.64	2.50	5.42	0.58	0.18	0.27	16.18	2.00	39.88
Lo28	19	13.14	13.84	15.33	18.71	1	249	SE	18.52	6.00	1.04	4.35	2.39	0.90	0.14	0.15	7.76	2.00	46.24	4.04	6.40	0.45	1.03	3.39	1.00	0.12	0.17	10.04	2.00	46.61
Lo29	19	13.41	15.40	18.10	22.09	4	362	NW	28.20	5.30	1.32	6.68	2.18	0.83	0.41	0.14	11.46	2.00	31.07	8.94	4.90	0.41	3.38	1.22	1.19	0.37	0.17	10.14	2.00	29.10
Lo30	21	13.50	16.70	21.27	24.84	3	264	E	16.88	5.60	0.99	2.68	4.56	0.86	0.37	0.15	9.77	2.00	60.82	9.49	4.80	0.50	1.60	1.34	0.91	0.28	0.15	8.67	2.00	30.90
Lo31	15	10.45	10.17	12.27	16.61	4	305	E	12.74	6.00	0.93	3.08	1.54	1.00	0.20	0.13	4.17	3.00	69.13	7.10	5.30	0.31	0.98	0.66	1.24	0.23	0.14	11.24	2.00	20.22
Lof1	29	37.42	25.13	25.69	26.06	1	379	S	34.70	6.00	1.70	16.20	7.62	1.92	0.17	0.03	14.69	1.80	66.22	13.60	5.70	0.70	4.35	3.33	1.96	0.14	0.04	11.44	1.00	47.87
Lof2	7	14.85	12.49	15.42	28.11	2	393	S	45.70	6.10	2.30	2.05	10.48	3.64	0.12	0.03	25.60	2.00	55.79	25.30	5.60	1.30	1.15	6.37	3.59	0.04	0.03	22.66	0.90	44.24
Lof3	29	33.55	21.75	22.28	22.60	3	398	SW	33.57	6.76	1.68	1.45	8.76	1.48	0.66	0.08	21.19	7.00	51.86	16.25	6.36	0.81	1.20	5.98	1.52	0.48	0.10	20.46	5.00	39.48
Lof4	25	21.96	16.88	18.17	19.65	4	484	W	33.14	5.48	1.66	6.55	2.53	0.89	0.37	0.05	9.43	12.00	40.67	13.74	5.45	0.69	3.60	1.12	0.64	0.32	0.04	10.17	3.00	20.85
Lof5	20	16.40	14.87	17.07	20.37	3	438	NE	21.47	5.81	1.07	3.70	2.17	0.83	0.31	0.05	6.25	7.00	53.81	0.34	6.36	0.02	2.25	1.47	0.63	0.12	0.05	5.51	2.00	41.26
Lof6	28	23.33	17.35	18.01	18.55	15	491	S	5.85	5.00	0.76	5.25	0.62	0.37	0.17	0.13	6.21	2.00	20.96	19.38	5.60	0.52	6.98	1.48	0.71	0.25	0.14	8.00	2.00	32.14
Lof7	28	24.92	17.46	18.06	18.60	2	469	S	22.98	5.90	1.34	3.83	2.01	1.81	0.49	0.14	15.96	4.00	27.90	7.20	4.90	0.54	1.48	0.52	1.66	0.49	0.17	16.23	2.00	17.47
Lof8	19	15.37	14.99	17.10	20.87	3	480	W	17.61	5.70	0.88	4.60	1.69	0.67	0.38	0.13	9.92	3.00	29.09	5.81	5.20	0.30	5.63	1.04	0.56	0.27	0.14	7.14	2.00	28.33
Lof9	19	16.12	16.98	20.04	24.46	6	469	W	20.83	5.70	1.10	4.70	2.33	0.72	0.37	0.13	10.38	3.00	34.20	5.16	4.70	0.34	1.45	0.63	0.52	0.29	0.12	12.20	2.00	12.84
Lof10	7	11.42	9.45	12.07	22.00	3	433	NE	22.33	5.70	1.36	6.05	2.79	1.40	0.71	0.14	15.64	4.00	32.21	7.62	4.70	0.54	105.00	0.69	1.60	0.37	0.13	19.27	2.00	14.48
Lof11	7	12.22	10.02	11.40	20.78	13	454	SW	22.18	5.90	1.44	6.10	5.78	1.87	0.81	0.15	21.73	3.00	39.67	8.55	5.60	0.66	1.98	3.79	1.91	0.41	0.17	17.28	2.00	36.40
Lof12	26	28.22	21.28	22.15	23.55	8	493	SW	33.51	6.10	1.58	2.28	4.72	1.42	0.44	0.14	16.30	6.00	41.24	9.90	4.80	0.64	0.78	1.48	1.37	0.14	0.14	18.29	3.00	17.14
Lof13	24	27.19	18.65	18.80	20.70	0	474	NA	24.53	6.40	1.35	5.20	4.12	1.19	0.24	0.15	11.91	5.00	47.90	5.56	4.80	0.39	1.33	1.15	1.59	0.14	0.13	11.59	2.00	25.99
Lof14	22	17.35	14.63	16.59	18.98	11	456	S	30.50	5.50	1.49	5.33	1.94	1.36	0.68	0.13	12.74	4.00	32.25	9.52	4.90	0.52	1.55	0.86	1.74	0.89	0.14	12.40	2.00	29.32
Lof15	30	29.01	19.56	19.90	19.90	5	356	SE	6.99	5.80	1.16	2.25	1.88	1.89	0.31	0.13	13.06	3.00	32.14	5.20	5.50	0.36	2.63	0.73	1.65	0.40	0.13	10.80	2.00	26.86
Lof16	30	24.91	17.86	19.40	19.40	6	380	N	19.54	5.50	1.24	3.60	2.04	2.02	0.30	0.14	12.74	3.00	35.31	6.21	4.90	0.46	1.18	1.02	1.37	0.25	0.14	14.73	2.00	18.85
Lof17	30	29.06	20.73	21.80	21.80	2	373	W	23.62	6.20	1.25	0.28	2.96	1.57	0.78	0.13	12.57	4.00	43.33	22.32	6.10	0.80	0.88	4.37	1.36	0.54	0.13	13.60	4.00	47.11
Lof18	9	13.17	11.01	12.70	21.16	1	384	SW	17.17	6.00	1.04	1.98	3.65	1.16	0.18	0.16	11.66	2.00	44.16	5.88	5.50	0.54	0.80	3.20	1.87	0.12	0.15	14.19	2.00	37.60
Lof19	9	12.62	10.82	12.90	21.49	4	387	NW	19.60	5.80	1.32	2.05	5.60	2.00	0.27	0.17	20.50	3.00	14.62	10.99	5.60	0.64	1.58	4.21	2.48	0.23	0.33	24.67	3.00	29.41
Lof20	30	30.77	21.45	22.34	22.34	7	386	SE	28.52	6.40	1.79	2.05	7.99	2.49	0.60	0.16	29.03	4.00	37.70	14.24	6.20	0.82	0.53	6.73	2.68	0.28	0.23	30.59	3.00	32.43

(Continued on next page)

Appendix Table. Dataset used in this study (Continued)

Plot	Age	DBH (cm)	H (m)	DTH (m)	SI	Slope (deg)	Elevation (m)	Aspect	Soil depth 0 cm-20 cm OM ($g\ kg^{-1}$)	pH	Total N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Exch. Ca ($cmolc\ kg^{-1}$)	Exch. Mg ($cmolc\ kg^{-1}$)	Exch. K ($cmolc\ kg^{-1}$)	Exch. Na ($cmolc\ kg^{-1}$)	CEC ($cmolc\ kg^{-1}$)	EC ($mS\ m^{-1}$)	BS (%)	Soil depth 40 cm-60 cm OM ($g\ kg^{-1}$)	pH	Total N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Exch. Ca ($cmolc\ kg^{-1}$)	Exch. Mg ($cmolc\ kg^{-1}$)	Exch. K ($cmolc\ kg^{-1}$)	Exch. Na ($cmolc\ kg^{-1}$)	CEC ($cmolc\ kg^{-1}$)	EC ($mS\ m^{-1}$)	BS (%)
Nob1	13	9.90	11.50	15.57	22.40	0	205	NA	27.60	5.20	1.40	1.80	3.77	1.29	0.07	0.02	11.08	1.00	46.48	9.30	4.80	0.50	1.30	2.45	1.40	0.06	0.03	13.06	0.40	30.18
Nob2	16	15.20	16.10	19.61	25.81	6	220	NE	31.70	6.00	1.60	1.30	8.77	1.98	0.11	0.02	16.79	2.10	64.78	9.80	6.20	0.50	0.90	6.64	2.06	0.05	0.03	15.18	1.10	57.81
Nob3	16	15.90	15.80	17.28	22.74	0	212	NA	29.60	5.80	1.50	2.35	8.29	2.91	0.08	0.06	18.41	1.40	61.65	14.30	5.30	0.70	1.20	6.53	3.72	0.06	0.20	20.58	0.80	51.06
Nob4	16	10.50	11.60	15.11	19.88	4	212	N	25.90	5.90	1.30	3.95	6.43	2.00	0.06	0.03	13.13	1.80	64.91	9.70	5.20	0.50	1.50	3.04	2.18	0.04	0.03	13.34	1.40	39.61
Nob5	16	10.00	11.50	15.08	19.85	0	233	NA	31.60	5.50	1.60	4.70	5.21	1.65	0.09	0.03	12.24	1.10	57.05	12.00	4.70	0.60	2.35	2.22	1.56	0.07	0.03	12.01	0.80	32.25
Nob6	16	10.50	12.50	17.62	23.19	0	226	NA	14.70	5.50	0.70	2.15	3.04	0.73	0.11	0.02	6.81	1.00	57.31	6.90	5.50	0.40	1.40	4.13	0.68	0.01	0.03	7.45	0.80	65.10
Nob7	16	10.13	10.94	17.51	23.04	10	265	N	8.90	6.20	0.40	2.30	8.74	1.69	0.12	0.03	14.26	2.60	74.17	10.70	5.90	0.50	1.00	6.00	2.29	0.05	0.03	13.16	1.60	63.63
Nob8	16	12.71	15.10	22.22	29.24	5	267	E	46.40	6.40	2.30	5.75	18.01	3.86	0.14	0.11	30.28	4.40	14.20	21.40	5.90	1.10	1.50	17.48	4.22	0.10	0.08	34.18	20.00	64.02
Nob9	17	17.88	16.90	20.24	25.94	4	247	S	16.20	5.70	0.80	0.75	4.70	1.71	0.17	0.03	16.57	4.30	39.93	18.70	5.90	0.90	0.03	3.81	1.42	0.03	0.02	20.28	4.00	26.05
Nob10	17	10.57	12.61	16.18	20.74	11	289	SW	43.31	6.80	2.17	2.70	6.27	1.50	0.38	0.09	17.03	11.00	48.40	16.42	6.39	0.82	1.60	3.79	1.51	0.21	0.09	14.58	6.00	38.42
Nob11	18	12.10	13.37	17.03	21.28	3	222	N	23.42	6.42	1.17	3.75	4.49	1.21	0.22	0.07	11.88	8.00	50.45	6.95	4.97	0.35	2.40	2.49	1.27	0.23	0.09	11.88	2.00	34.28
Nob12	16	11.36	11.86	14.93	19.65	1	240	S	27.82	5.74	1.39	5.45	5.25	1.27	0.16	0.07	13.60	7.00	49.65	11.66	5.39	0.58	3.95	5.16	1.25	0.15	0.08	12.13	5.00	54.79
Nob13	16	10.01	9.76	13.91	18.31	1	229	S	13.44	5.10	0.67	2.10	1.42	0.55	0.16	0.06	8.98	2.00	25.54	11.15	4.91	0.56	1.55	1.91	0.60	0.13	0.04	8.21	2.00	32.62
Nob14	16	11.37	12.69	14.94	19.66	1	209	NE	23.56	5.68	1.18	2.30	3.71	1.38	0.18	0.07	12.13	5.00	44.08	10.10	5.56	0.50	1.65	2.78	1.35	0.16	0.13	13.60	2.00	32.50
Nob15	15	15.60	17.09	21.78	29.48	2	207	E	22.64	6.28	1.13	58.55	5.78	1.12	0.49	0.12	11.64	8.00	64.57	6.76	6.02	0.34	52.65	4.55	1.16	0.41	0.09	12.37	3.00	50.25
Nob16	18	11.70	13.80	17.87	22.33	2	236	W	25.03	5.79	1.25	2.30	4.03	1.39	0.17	0.06	11.88	3.00	47.55	12.02	5.55	0.60	1.60	2.89	1.41	0.14	0.13	13.11	3.00	34.97
Nob17	17	12.46	14.27	15.90	20.38	2	222	E	26.67	6.38	1.33	2.65	5.76	1.42	0.32	0.08	14.09	4.00	53.83	11.09	5.73	0.55	1.80	3.48	1.45	0.27	0.13	14.33	3.00	37.19
Nob18	17	12.37	14.72	18.82	24.12	2	218	N	24.04	6.29	1.20	2.30	5.08	1.35	0.23	0.10	13.84	2.00	48.85	13.61	5.16	0.68	1.70	3.55	1.37	0.15	0.10	16.05	5.00	32.28
Nob19	18	8.96	10.76	14.13	17.66	2	225	SE	10.85	6.07	0.54	1.85	7.89	1.32	0.16	0.08	17.03	5.00	55.49	19.62	6.03	0.98	1.65	7.56	1.35	0.10	0.11	16.29	2.00	55.97
Nob20	18	14.21	16.73	19.17	23.96	3	210	N	31.55	6.56	1.58	6.45	6.41	1.34	0.24	0.06	12.86	14.00	62.54	10.37	6.28	0.52	1.90	4.78	1.42	0.17	0.07	11.39	6.00	56.58
Nob21	18	18.01	17.92	20.00	25.00	0	205	NA	27.10	6.40	1.36	3.05	4.55	1.32	0.19	0.05	10.90	5.00	56.00	6.95	6.12	0.35	2.45	3.51	1.45	0.12	0.06	11.39	3.00	45.13
Nob22	17	11.65	12.57	15.36	19.69	3	208	SW	25.40	5.68	1.27	3.85	2.39	1.18	0.17	0.04	11.64	6.00	32.54	5.39	5.13	0.27	2.15	1.31	1.30	0.11	0.04	9.19	4.00	30.12
Nob23	14	9.36	8.84	11.80	16.45	1	214	N	8.95	5.39	0.45	2.95	0.68	0.40	0.11	0.02	6.25	3.00	19.44	2.54	5.18	0.13	2.10	0.84	0.63	0.08	0.03	5.27	2.00	29.92
Nob24	15	10.91	13.42	16.14	21.84	2	207	S	35.27	6.32	1.76	3.35	7.34	0.92	0.09	0.06	14.82	9.00	56.72	19.36	6.45	0.97	2.10	8.82	0.90	0.10	0.05	18.58	4.00	67.75
Ud1	20	16.18	16.26	21.71	25.90	0	199	NA	5.85	5.50	0.60	1.40	0.54	0.24	0.05	0.06	1.47	2.00	60.44	3.27	5.20	0.29	1.00	0.51	0.26	0.08	0.08	1.51	1.00	61.47
Ud2	22	14.56	16.07	18.92	21.64	4	211	NE	9.22	6.00	0.69	3.33	1.66	0.59	0.06	0.06	2.55	2.00	89.88	5.87	5.50	0.21	3.00	1.36	0.55	0.06	0.06	2.63	1.00	77.16
Ud3	20	14.53	15.54	19.33	23.06	0	178	NA	11.94	5.50	0.67	2.95	1.24	0.40	0.06	0.06	3.59	1.00	49.19	4.03	5.20	0.23	1.80	1.47	0.62	0.06	0.05	3.74	2.00	58.79
Ud4	20	12.21	14.83	20.20	24.10	0	205	NA	12.92	5.80	0.73	3.00	2.11	0.56	0.09	0.07	2.96	2.00	95.48	3.36	5.50	0.27	0.95	1.47	0.66	0.07	0.05	2.92	2.00	76.98
Ud5	20	11.76	11.85	14.83	17.69	1	179	N	13.48	5.50	0.84	2.10	2.39	1.08	0.12	0.06	5.57	2.00	65.60	5.78	5.20	0.36	0.50	2.17	1.37	0.12	0.10	8.17	1.00	46.01
Ud6	20	9.60	8.26	12.51	14.93	1	197	NW	8.32	5.50	0.68	1.65	0.58	0.65	0.10	0.06	2.67	2.00	52.13	8.23	5.00	0.34	1.15	0.93	1.06	0.12	0.06	5.39	1.00	40.31
Ud7	20	9.90	8.52	11.42	13.62	2	195	N	10.56	5.50	0.70	2.20	0.83	0.67	0.11	0.08	2.53	2.00	66.53	4.88	7.10	0.26	0.85	0.75	0.98	0.07	0.05	4.55	1.00	40.74
Ud8	20	13.71	13.79	16.73	19.96	1	200	E	4.04	5.90	0.88	0.80	3.50	1.16	0.09	0.04	5.10	3.00	93.90	7.55	5.30	0.38	0.70	2.24	1.09	0.08	0.07	4.19	1.00	83.17
Ud9	22	22.00	20.61	26.46	30.27	9	310	W	13.78	6.00	0.90	2.75	4.76	1.24	0.21	0.05	8.94	5.00	70.06	7.30	5.00	0.43	0.65	1.51	1.01	0.17	0.08	8.00	2.00	34.48
Ud10	19	17.13	17.17	20.88	25.48	12	352	N	12.19	6.10	0.91	1.10	6.41	1.49	0.07	0.09	7.90	4.00	101.00	9.11	5.10	0.58	0.50	4.10	1.49	0.04	0.07	8.39	4.00	67.95
Ud11	20	16.83	18.36	22.45	26.78	4	254	S	11.16	5.70	0.85	2.65	5.38	1.03	0.13	0.04	7.72	4.00	85.21	9.39	5.70	0.55	1.15	3.96	1.02	0.09	0.06	7.41	2.00	69.25
Ud12	19	13.77	13.89	17.24	21.04	3	281	NW	9.44	5.80	0.82	2.55	3.71	1.16	0.10	0.09	8.57	3.00	59.04	10.31	5.10	0.52	1.30	1.94	0.86	0.04	0.06	6.94	2.00	41.62