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Original Article

Estimating site index from ecological factors for industrial tree plantation species in Mindanao, Philippines

Analyn L. CODILAN*1,*2, Tohru NAKAJIMA*1, Satoshi TATSUHARA*1,
Norihiko SHIRAISHI*1

Introduction

Forest plantations are mainly developed for wood production but may also be established to provide a wide array of services like wildlife habitat, biodiversity, aesthetics and other services (PACKALEN *et al.*, 2011). The rapid increase in the world's population amidst the issue of increasing forest loss and degradation (FOX, 2000) amplifies the major role of forest plantations for timber production in meeting the world's increasing demand for wood. This issue and the increasing demand on forestlands for competing land uses serve as impetus for intensive management of plantation forests.

In intensive forest plantation management, higher growth rates could be achieved by concentrating timber production on best-adapted sites (FOX, 2000) or when species are properly matched with their site requirements (HARRISON and HERBOHN, 2000). In concept, the productivity of plants decrease when an environmental factors is outside the optimum range for growth of the plant (CHEN *et al.*, 1998). This is usually accomplished through identification and evaluation of site quality specific to the target tree species. Site quality is defined as the innate productive capacity of the land area (CLUTTER *et al.,* 1983). Its evaluation characterizes the potential site productivity under a specified management regime and identifies associations between soil-site features and tree growth (FOX, 2000). The information derived from site quality evaluation aids forest managers in evaluating silvicultural implications (LOUW and SCHOLES, 2002), assists in making cost-effective decisions about land-use and silvicultural investment levels (MCKENNEY and PEDLAR, 2003) and facilitates management decision-making and development of new technology (FOX, 2000).

Knowledge on site quality for forest management has been properly and thoroughly stressed in many studies in the past (CHEN *et al.*, 1998; KAYAHARA *et al.*, 1998; SEYNAVE *et al.*, 2005; MITSUDA *et al.*, 2007; BOSELA *et al.*, 2013). In terms of timber production, the widely used measure of site quality is site index, which is usually defined as the estimated height of the dominant trees at a site at a particular reference or base age (CARTER and KLINKA, 1990; NIGH, 1995; CARMEAN, 1996; IVERSON *et al.*, 1997; CHEN *et al.*, 1998; RICHARDSON *et al.*, 1999; DAVIS *et al.*, 2001; HUI-YAN *et al.*, 2001; MITSUDA *et al.*, 2001; NIGH, 2002; MCKENNEY and PEDLAR,

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＊1 Laboratory of Forest Management, Department of Forest Science, Graduate School of Agricultural and Life Sciences, The University of Tokyo

＊2 Institute of Renewable Natural Resources, College of Forestry and Natural Resources, University of the Philippines Los Baños Laguna

2003; SEYNAVE *et al.*, 2005; WANG *et al.*, 2005; MATHIASEN *et al.*, 2006;MITSUDA *et al.*, 2007; NUNES *et al.*, 2011; PACKALEN *et al.,* 2011; CRECHI *et al.*, 2011; BOSELA *et al.*, 2013). The extensive use of site index in site quality evaluation is due to its close relation to volume growth and dominant height of most tree species in even aged stands which is relatively unaffected by stand density and species mixture (CARTER and KLINKA, 1990; CARMEAN, 1996; FORSS *et al.*, 1996; RICHARDSON *et al.*, 1999).

There are two basic methods in evaluating site quality in terms of site index: direct (phytocentric) and indirect (geocentric) (CLUTTER *et al.*, 1983; SOCHA, 2008; BOSELA *et al.*, 2013). The former involves direct measurement of the average height of dominant trees at a certain base age while the latter associates site index with ecological factors. The direct approach provides a simple and efficient tool for estimating site index using height growth models for mature stands or using growth intercept models for young stands with free-growing trees (CHEN *et al.*, 1998). However, it has some drawbacks. Direct measurement of site index cannot be done in tree-less areas or in sites where the concerned species is not present (CHEN *et al.*, 1998; CORONA *et al.*, 1998; MCKENNEY and PEDLAR, 2003; WANG *et al.*, 2005; BOSELA *et al.*, 2013). It also imposes strict stand characteristic restrictions (age and stocking) before it can be successfully applied to predict site quality in other areas. In cases like these, the indirect site index measurement seems to be more favorable.

The indirect method assumes that site productivity is determined by factors directly affecting plant growth which are solar radiation, temperature, water, nutrients, soil aeration, and biotic interactions (CHEN *et al.*, 1998). There are two main approaches in implementing indirect site index measurement: synoptic and analytic. In the synoptic approach, site index is correlated with site or soil classes, whereas the analytic approach consists of modelling the site index as a function of various ecological, topographical, and soil variables (SEYNAVE *et al.*, 2005; SOCHA, 2008; BOSELA *et al.*, 2013).

A wealth of studies had been published on evaluating site index using the analytic approach, particularly for temperate tree species. These studies used various kinds and different categories of ecological variables to predict site index variability. Most of these studies employed multiple regression analysis that used a number of topographic, soil physical, and soil chemical properties as independent variables to predict site indices (RICHARDSON *et al.*, 1999; MITSUDA *et al.*, 2001; BOSELA *et al.*, 2013). One of the early works on this subject was that of HAGGLUND and LUNDMARK (1977), which expressed in mathematical functions the dependence of site index of Scots pine and Norway spruce in Sweden with factors such as geographical location, ground vegetation and soil properties.

The commonly investigated ecological variables are topography, climate and soil (CHEN *et al.*, 1998). Examples of these variables are latitudinal and longitudinal gradients, elevation, slope, aspect, rainfall, temperature, soil moisture, soil nutrients, soil depth, physical and chemical soil properties. Succeeding studies investigated site correlations with topographical exposure (CORONA *et al.*, 1998; CURT *et al.*, 2001), growing season water deficit (CARTER and KLINKA, 1990), soil aeration regimes (WANG and KLINKA, 1996), forest floor characteristics and foliar nutrients (CHEN *et al*., 1998), biogeoclimatic zones (CHEN *et al*., 2002), understorey vegetation (SEYNAVE *et al*., 2005), solar radiation index (MITSUDA *et al*., 2007), soil parent rock (SOCHA, 2008), and length of growing season (BOSELA *et al*., 2013).

In the advent of technological advances, tools like geographic information systems (GIS) and remote sensing (RS) made estimation of ecological characteristics on large areas more convenient limiting the need for extensive field surveys. This made possible the calculation of ecological variables from remotely-sensed data and digital elevation models (DEM). As a result more ecological factors were being added to model site index variability. IVERSON *et al*. (1997) used GIS to develop an integrated moisture index (IMI) from DEM of different resolutions, which was then used to predict oak (*Quercus* spp.) site index and species composition for forests in Ohio. In this study, several landscape features such as slope-aspect shading index, cumulative flow of water downslope, curvature of the landscape, and water-holding capacity of the soil were used to create the IMI. The statistical relationships obtained were then imported GIS to come up with maps of site index and composition. In 2006, MINGDONG *et al*. correlated spruce site index with remotely-sensed data such as normalized difference vegetation index (NDVI) and soil adjust vegetation index (SAVI). In Japan, site index models for Sugi (*Cryptomeria japonica*) (MITSUDA *et al*., 2007) and Japanese larch (MITSUDA *et al*., 2001) were constructed from DEM-based environmental factors.

In the Philippines, the rapid decline of forest cover due to illegal and commercial exploitations impelled the massive reforestation programs for timber production and environmental purposes (HARRISON and HERBOHN, 2000). Several introduced species such as G*melina arborea, Paraserianthes falcataria, Tectona grandis, Swietenia macrophylla* and *Acacia mangium* and native species *Eucalyptus deglupta, Melia dubia* and *Endospermum peltophorum* were used in the reforestation and plantation development programs. However, poor growth and vigor frustrate these efforts. One reason is improper site-species matching (HARRISON and HERBOHN, 2000) which could be attributed to lack of knowledge on site productivity of reforestation and plantation areas. Most, if not all, efforts to measure species-specific site index in the Philippines used the direct approach. Unfortunately, there is a dearth of studies investigating the relationship between site index and site factors of major plantation species, thus the lack of information on site productivity of candidate sites for reforestation and plantation development. Hence, this study aims to fill that knowledge gap and provide managers a practical way of determining site productivity that could then be used for site-species matching and other related decisions.

The objectives of the study are (1) to identify the main ecological factors affecting site index variability of four major industrial tree plantation species in Mindanao region, Philippines - *Paraserianthes falcataria, Endospermum peltatum, Acacia mangium* and G*melina arborea*; and (2) to develop best-fit site index predictor model for each target species.

Study Site and Method

Study Site

The study site is a 5,000 ha forest land in the province of Agusan del Sur, Mindanao, Philippines (Fig. 1). It is located at 8° 20’ to 8° 25’ north latitude and at 125°33’ to 125°40’ east longitude. The general terrain is gently sloping to moderately rolling with a mean elevation of 150 meters above sea level. The mean temperature is 26.6 ℃, while mean annual rainfall is 2,900 mm.

Back in 1976, the site was a logged-over area converted to an industrial tree plantation of matchwood and softwood tree species. For more than 25 years, the site is managed under a tenurial instrument called the Integrated Forest Management Agreement (IFMA). The objective of this IFMA is to develop and manage about 70% of the area (~3,500 ha) as industrial plantation forests of fast growing softwood species like Falcata (*Paraserianthes falcataria*), Gubas (*Endospermum peltatum*), Gmelina (*Gmelina arborea*) and Mangium (*Acacia mangium*). These tree species are cultivated for various purposes such as pulpwood and raw material for matchstick and veneer production. The remaining area of residual forest (30%) is being managed as protection forest. Silvicutural treatments applied on the plantation areas include pruning during the early stage of the plantation for trees ≤ 2 meters in height to minimize wood knots and application of fertilizers on young and seemingly poorly performing plantations. Thinning

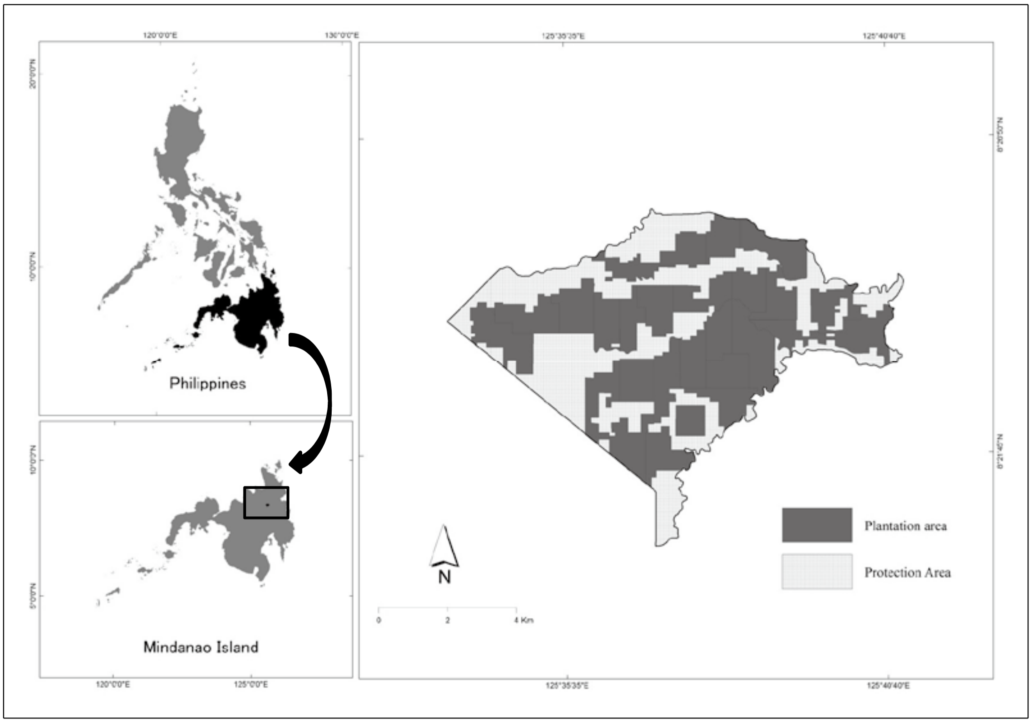

Fig. 1. Location of the study area in Agusan del Sur, Mindanao, Philippines

operations are not practiced.

Data Collection

Data from inventory activities conducted in 2007, 2011 and 2013 were used in the study. In the inventory, 0.1-0.2 ha sample plots were laid out throughout the study area, tree diameter at breast height (DBH) and total height (TH) for all standing trees were measured. Plot locations were recorded on maps and plot ages were verified from plantation maps and planting records. Inventory plots located inside the plantation areas containing the target species were selected as sample plots for the study. The inventory plots which contain an overlap of target species were segregated and the characteristics were determined according to the specific target species. The sample plots were randomly split into two sets, one for model development and the other set for model validation. The tallest trees of each species from each sample plot were chosen as site trees and their mean height was determined to obtain an estimate of the dominant height. Summary statistics of the sample plots used and the corresponding site factors are shown in Table 1.

The sample plots are well-distributed over the study area to cover a wide range of variation in each ecological factor. However, there are still some cases where only a small portion of the site factor variability was considered. But in general, the study considered a sufficient proportion of the possible values of ecological factors throughout the study area. Further, the samples were located in plantation areas where productivity related planning and evaluation were focused.

Ecological factors

Raster maps of ecological factors were derived and processed from an ASTER GDEM with 30 m resolution and processed in ArcGIS 10.2. The following ecological factors were used in this study: elevation (E), slope (S), topographic position index (TPI), curvature (C), wetness index (WI), sunlight duration (SD), direct solar radiation (SR), topographic exposure (TPX), and annual rainfall (RAIN). These factors were chosen based on the results of previous studies on their potential effect on site index. In addition, most of them can be derived easily from DEM data. The factors were categorized into topography, soil moisture, solar and wind and climate variables.

Topographical variables include elevation (E), slope (S) and topographic position index (TPI). E was obtained from the DEM while S was calculated as the maximum change in elevation over the distance between the cell and its neighbors in a 3-by-3 cell environment. A lower slope value indicates a flatter terrain while a higher value represents steep slopes. On the other hand, TPI was computed as the difference between a cell elevation value and the average elevation of the neighborhood around that cell. A 5-cell circular neighborhood was used in the study. Positive TPI values mean the cell is higher than its surroundings while negative values mean it is lower than the neighboring cells. TPI values near 0 mean that the elevation is close to the mean elevation of the neighbor cells, which usually happens in flat or mid-slope areas. TPI was calculated using the Land facet corridor extension toolset created by MAJKA *et al*. (2007).

Table 1. Summary statistics of sample plots used for site index model development

Variables	*P. falcataria*		*E. peltatum*		*A.mangium*		*G. arborea*	
	n_m= 286		n_m= 238		n_m= 53		n_m= 75	
	n_v = 52		n_v = 51		n_v = 18		n_v = 25	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Tree Density (tree/ha)	321	40-515	187	40-700	44	30-110	236	30-813
Average DBH (cm)	26	17-32	24	16-34	22	17-30	24	17-29
Average TH (m)	15	9-18	14	9-20	13	8-18	13	11-15
Basal Area per ha (m^2/ha)	17	1-33	8	1-42	2	1-4	10	1-40
Total Volume per ha (m^3/ha)	170	8-364	75	6-389	16	8-40	78	5-331
Age (years)	8	3-9	5	2-14	9	4-13	8	3-13
Dominant DBH (cm)	39	17-55	30	17-46	25	20-40	27	17-42
Dominant TH (m)	19	11-25	17	11-22	15	11-22	16	12-20
Site Index (m)	21	16-27	33	16-47	15	8-26	19	14-26
Elevation (m)	109	62-181	119	66-183	114	67-172	130	57-198
Slope (°)	7	2-25	10	2-26	8	2-19	12	2-33
Topographic Position Index (m)	1	-15-27	1	-20-32	1	-7-15	2	-15-15
Curvature	-0.03	-1.8-0.9	-0.05	-1.8-1.4	0.01	-0.4-0.5	-0.02	-0.9-0.9
Wetness Index	7	4-11	7	5-11	7	5-9	6	5-10
Sunlight Duration (hours/year)	4191	3759-4337	4099	3375-4333	4162	3875-4300	4094	3535-4329
Direct Solar Radiation (kcal/cm^2)	119	110-122	118	101-122	119	114-122	117	99-122
Topographic Exposure	215	198-217	213	196-217	215	206-217	211	184-217
Annual Rainfall (mm)	2913	2837-3013	2881	2787-2982	2874	2786-3002	2843	2786-3013

n_m= number of sample plots used for model development, n_v = number of validation plots

In the absence of data on soil characteristics, DEM-derived ecological variables related to soil moisture such as curvature (C) and wetness index (WI) were used. C is defined as the inclination of the slope, which describes a landform (IVERSON *et al.*, 1997; MITSUDA *et al.*, 2001). C values used in this study were derived from the profile curvature output raster of the curvature tool. Positive curvature values indicate that a surface is upwardly concave while a negative curvature indicates that the surface is upwardly convex. A value of 0 means that the surface is flat. Curvature is used to model exposed and sheltered sites as well as flow acceleration. On the other hand, Wetness Index (WI) is calculated using the formula, $WI= \ln (A_s/\tan ß)$, where A_s is the catchment area and ß represents the slope gradient. This equation assumes steady state conditions and uniform soil properties. It is used to predict zones of saturation along drainage paths and in zones of water concentration in landscapes (WILSON and GALLANT, 2000). Wetness index was calculated from a filled DEM by filling in sinks using Hydrology toolset to correct for erroneous flow directions. The final wetness index map was then computed from flow-path lengths and upslope contributing areas. Increasing WI values are observed from the ridge to valley bottoms and river beds.

The probable solar and wind related effects were investigated using sunlight duration (SD), direct solar radiation (SR) and topographic exposure (TPX) variables. SD and SR were derived using the solar radiation toolset, where SR was calculated as the incoming direct solar radiation from a raster surface considering latitudinal area location, slope and aspect data. SR was estimated for the whole year. Increasing SD and SR values mean longer and higher exposure to solar radiation, respectively. Meanwhile, TPX describes the protection or exposure of a given site by the surrounding topography. This factor gives an idea of the degree of openness of a given site, which relate to wind and water dynamics. TPX in this study was modeled using the shade topography averaged from 16 maps of the cardinal and ordinal directions (N, NE, E, SE, S, SW, W, NW) using 45° and 90° elevation angle for each azimuth direction. Increasing TPX values indicate increasing levels of exposure.

The climatic ecological variable represented by the amount of annual rainfall (RAIN) was used to determine the effect of climate variability on site index. The_availability of climate data in the Philippines is generally limited and for this study the data of mean annual rainfall from three weather stations with the shortest proximity to the study area were used. These weather stations are located in (1) Butuan City, Agusan del Norte (08°56’ N Lat, 125°31’ E Long), (2) Malaybalay City, Bukidnon (08°09’ N Lat, 125° 05’ E Long) and (3) Hinatuan City, Surigao del Sur (08°22’ N Lat, 126°20’ E Long). The distances between the study area and weather stations 1, 2 and 3 are about 57 km, 60 km and 72 km, respectively. Weather station 1 is about 98 km and 109 km away from weather stations 2 and 3, respectively. On the other hand, the distance between weather stations 2 and 3 is about 139 km. Rainfall data from 2002-2012 from these weather stations were collected from the database of Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAG-ASA) and values were averaged to determine the 10-year mean values. The values were then interpolated using inverse distance weighted (IDW) function to estimate the local climatic conditions in the study area.

Table 2. Site index equations used to determine measured site index for each target species

Species	Equation	Base Age	Author
P. falcataria	$\log SI = 0.41834 + \log H - 0.41834 \log A$	10	(REVILLA, 1974)
E. peltatum	$\log SI = 0.69879 - 0.59416 \log A + \log H$	15	(RAMOS, 1977)
A. mangium	$\log SI = \log H + 0.8955(\log BA - \log A)$	8	(PALMA *et al.*, 2006)
G. arborea	$\log SI = - 0.06139 + \log H + 0.92094/A$	15	(LINGAN, 1979)

SI = site index (m), H = dominant height (m) and A = age in years

Data Analysis

In this study, site index was related to ecological variables by first determining the measured site index value of each sample plot for the respective target species using published site index equations at a certain base age (Table 2). Then, a correlation analysis was conducted to investigate the degree of linear relationship between and among the variables. The following linear relationship between SI and ecological factors was assumed,

$$SI = \alpha + \beta X_1 + \beta X_2 + \beta X_2 + \dots + \varepsilon$$

where, site index (SI) is a multiple linear function of ecological factors (X_i), their coefficients (β_i) and error (ε) (CORONA *et al.*, 1998; FONTES *et al.*, 2003; ERCANLI *et al.*, 2008).

Since the form of the model is unknown, several procedures were employed to select the variables that will be considered in the best model selection. The variable selection procedures included an exhaustive search for the best variable subsets using an efficient branch-and-bound algorithm with Bayesian Information Criterion (BIC) results and backward stepwise regression using Akaike Information Criterion (AIC). The ecological variables most frequently selected from the two procedures were tested using multiple linear regression analysis where the best predictor model was dictated by the regression statistics.

Multicollinearity among variables was minimized by dropping models whose beta-coefficients have conflicting signs and with very high variance inflation factor (VIF). A VIF value of more than 10 indicates an existence of serious multicollinearity problem and masks the true relationship between the predictor and response variables; so this should be carefully examined.

Regression analyses were performed for each set of grouped variables and their combinations to test the effect of different ecological variables on site index. The best fit model is then selected from all significant models based on the adjusted coefficient of determination (adjusted R^2) and standard error of estimate (SEE). Individual regression statistics such as standard regression coefficients (SRC) and partial coefficient of determination (PCD) for the best models were also estimated. The independent variables tested were measured in different units, so SRC is estimated to see the actual effect of each independent variable using the same unit. On the other hand, PCD reflects the actual prediction power of each independent variable on the response variable by withholding the impact of other independent variables in the model.

All statistical analyses were done using R (R CORE TEAM, 2013) in RStudio (RSTUDIO, 2012).

Table 3. Pearson’s correlation coefficient between site index of *P. falcataria* and ecological factors.

	SI	E	S	TPI	C	WI	SD	SR	TPX	RAIN
SI	1.00									
E	-0.41^{**}	1.00								
S	-0.13^{*}	0.29^{**}	1.00							
TPI	-0.13^{*}	0.15^{**}	0.18^{**}	1.00						
C	0.11	-0.17^{**}	-0.16^{**}	-0.66^{**}	1.00					
WI	0.27^{**}	-0.20^{**}	-0.53^{**}	-0.56^{**}	0.38^{**}	1.00				
SD	0.10	-0.11	-0.56^{**}	0.46^{**}	-0.37^{**}	0.00	1.00			
SR	-0.18^{*}	0.05	-0.62^{**}	-0.09	0.11	0.30^{**}	0.33^{**}	1.00		
TPX	0.08	-0.30^{**}	-0.95^{**}	-0.17^{**}	0.18^{**}	0.44^{**}	0.51^{**}	0.59^{**}	1.00	
RAIN	0.71^{**}	-0.79^{**}	-0.32^{**}	-0.05	0.13^{*}	0.20^{**}	0.26^{**}	0.01	0.29^{**}	1.00

** significant at α=0.01, * significant at α=0.05

Table 4. Pearson’s correlation coefficient between site index of *E. peltatum* and ecological factors.

	SI	E	S	TPI	C	WI	SD	SR	TPX	RAIN
SI	1.00									
E	-0.70^{**}	1.00								
S	-0.08	0.08	1.00							
TPI	-0.28^{**}	0.32^{**}	0.11	1.00						
C	0.16^{*}	-0.19^{**}	-0.09	-0.70^{**}	1.00					
WI	0.37^{**}	-0.43^{**}	-0.36^{**}	-0.60^{**}	0.32^{**}	1.00				
SD	-0.13^{*}	0.07	-0.45^{**}	0.58^{**}	-0.38^{**}	-0.22^{**}	1.00			
SR	-0.22^{**}	0.24^{**}	-0.72^{**}	0.13^{*}	-0.06	0.07	0.51^{**}	1.00		
TPX	0.04	-0.01	-0.96	-0.09	0.10	0.29	0.43^{**}	0.74^{**}	1.00	
RAIN	0.60^{**}	-0.44^{**}	-0.28^{**}	-0.17^{**}	0.13^{*}	0.20^{**}	-0.05	0.04	0.21^{**}	1.00

** significant at α=0.01, * significant at α=0.05

Results

Correlation Analysis

The relationships between site index and ecological factors for each species are given in Tables 3-6.

The site index of *P. falcataria* is positively correlated with WI and RAIN and is negatively correlated with E, S, TPI, and SR. It decreases with an increase in elevation (r=-0.41), slope (r=-0.13 and topographic position (r=-0.13). Similarly, site index decreases with an increase in exposure to direct solar radiation (r=-0.18). On the other hand, it increases with an increase in wetness index (r=0.27). Site index is also expected to increase with an increase in the amount of rainfall (r=0.71).

For *E. peltatum*, site index is found to be positively correlated with C, WI, and RAIN. On the other hand, it is negatively correlated with E, TPI, SD and SR. In terms of topography, site index decreases with both an increase in elevation and topographic position (E:r=-0.70; TPI:r=-0.28). In the same manner, site index is observed to be lower in areas with longer and higher exposure to sunlight (SD:r=-0.13; SR:r=-0.22). But site index is higher in concave areas (r =0.16), located near valley bottoms and rivers (r=0.37) and which receives ample amount of rainfall (r=0.60).

Table 5. Pearson's correlation coefficient between site index of *A. mangium* and ecological factors.

	SI	E	S	TPI	C	WI	SD	SR	TPX	RAIN
SI	1.00									
E	-0.54**	1.00								
S	-0.04	0.38**	1.00							
TPI	-0.13	0.31*	0.06	1.00						
C	-0.02	-0.07	-0.34**	-0.51**	1.00					
WI	0.13	-0.36**	-0.50**	-0.55**	0.40**	1.00				
SD	-0.09	-0.14	-0.66**	0.40**	-0.04	0.12	1.00			
SR	-0.40**	0.23	-0.46**	-0.13	0.27*	0.26	0.30*	1.00		
TPX	0.02	-0.32**	-0.96**	-0.08	0.37**	0.48**	0.60**	0.42**	1.00	
RAIN	0.43**	-0.80**	-0.49**	0.01	-0.06	0.25	0.38**	-0.07	0.40**	1.00

** significant at α=0.01, * significant at α=0.05

Table 6. Pearson's correlation coefficient between site index of *G. arborea* and ecological factors.

	SI	E	S	TPI	C	WI	SD	SR	TPX	RAIN
SI	1.00									
E	-0.49**	1.00								
S	-0.12	0.13	1.00							
TPI	-0.36**	0.50**	0.07	1.00						
C	0.22	-0.24*	0.00	-0.59**	1.00					
WI	0.43**	-0.46**	-0.56**	-0.61**	0.32**	1.00				
SD	-0.28*	0.16	-0.66**	0.49**	-0.42**	0.07	1.00			
SR	-0.16	-0.04	-0.75**	0.02	-0.11	0.33**	0.70**	1.00		
TPX	0.00	-0.05	-0.96**	-0.06	-0.01	0.47**	0.65**	0.80**	1.00	
RAIN	0.65**	-0.45**	-0.35**	-0.18	0.15	0.41**	0.02	0.11	0.23*	1.00

** significant at α=0.01, * significant at α=0.05

The site index of *A. mangium* showed significant positive correlation with RAIN variable and negative correlation with E and SR. It decreases with an increase in altitude (r=-0.54) and direct solar radiation (r=0.40). On the other hand, site index for this species is observed to increase with an increase in rainfall amount (r=0.43).

Lastly, for *G. arborea* the variables WI and RAIN displayed a significant positive relationship with site index whereas a negative relationship was observed with E, TPI, and SD. Site index decreases significantly with positive changes in elevation (r=-0.49) and topographic position index (r=-0.36). It is also observed to decrease in areas having longer exposure to sunlight (r=-0.28). On the contrary, it increases with wetness index value (WI:r=0.43) and at the same time with increasing rainfall amount (r=0.65).

Multiple Linear Regression Analysis

Site index variability for the target species was modeled using regression analysis per variable group, combination of ecological variables and common variable models. All accepted models are significant (p<0.000) and all variables of these models are significant at α=0.05.

Table 7. Regression statistics of site index model groups

Model group	No.	Variable	*P. falcataria*			*E.peltatum*			*A. mangium*			*G. arborea*		
			Adj. R^2	SEE	p-value	Adj. R^2	SEE	p-value	Adj. R^2	SEE	p-value	Adj. R^2	SEE	p-value
Topography	1	E	0.161	1.776	0.000	0.490	4.196	0.000	0.287	3.813	0.000	0.220	2.514	0.000
	2	E,S	-	-	-	-	-	-	0.319	3.727	0.000	-	-	-
Soil	3	WI	0.069	1.86	0.000	0.128	5.487	0.000	-	-	-	0.166	2.599	0.000
Wind	4	SD, SR	0.055	1.875	0.000	-	-	-	-	-	-	-	-	-
	5	SR,TPX	0.079	1.851	0.000	0.134	5.470	0.000	-	-	-	0.060	2.765	0.046
	6	SD, TPX	-	-	-	-	-	-	-	-	-	0.117	2.675	0.004
Climate	7	RAIN	0.504	1.358	0.000	0.358	4.709	0.000	0.168	4.122	0.001	0.437	2.136	0.000

Table 8. Form of the best-fit integrated models for each target species

Model No.	Species	Equation	Adj. R^2	SEE	p-value
8	a	$SI = -35.616 + 0.314\,(WI) - 0.225\,(SR) + 0.028\,(RAIN)$	0.576	1.256	0.000
9	b	$SI = -95.604 - 0.128\,(E) + 0.405\,(WI) - 0.222\,(SR) + 0.058\,(RAIN)$	0.609	3.677	0.000
10	c	$SI = 108.821 - 0.118\,(E) - 0.678\,(SR)$	0.360	3.615	0.000
11	d	$SI = -58.237 - 0.019\,(E) - 0.004\,(SD) + 0.034\,(RAIN)$	0.522	1.969	0.000

Species letters a,b,c,d correspond to the the following : a = *P. falcataria*, b = *E. peltatum*, c = *A. mangium*, d = *G. arborea*

Table 7 shows the list of all accepted models per variable group. In terms of topography, the single variable model using E (Model 1) is the only model that turned out to be significant for all species. Site index model combining E and S (Model 2) were significant for *A. mangium* only. Regressions of site index and soil moisture variables (C and WI) were not significant for all species where only the single variable model using WI (Model 3) were significant for *P. falcataria*, *E. peltatum* and *G. arborea*. On the other hand, regressions between site index and solar and wind related variables (SD, SR and TPX) appeared significant for *P. falcataria* (Model 4 and 5)*, E. peltatum* (Model 5) and *G. arborea* (Model 5 and 6) species only. The climatic model using RAIN variable (Model 7) is significant for all species.

For *P. falcataria* and *G. arborea*, the best performing model group is the climate model followed by the topography model. Model 7 can predict as much as 50% and 44% of the site index variability in *P. falcataria* and *G. arborea,* respectively while the prediction power of model 1 is only about 16-22%. The opposite is true for *E. peltatum* and *A. mangium* where topography models performed better than climate models. For *E. peltatum*, the adjusted R^2 value of model 1 (0.490) is higher than that of model 7 ($R_a^2 = 0.358$). Similarly for *A. mangium,* models 1 and 2 outperformed model 8 with $R_a^2 = 0.287$; 0.319 and SEE=3.813; 3.727, respectively. For all species, models related to soil moisture and solar and wind performed poorly, with predictive power of less than 17%.

The results of the regression between site index and the combination of ecological variables (Table 8) yield higher accountabilities than that of the regression on grouped variables. The

Table 9. Regression statistics of the best-fit integrated models for each target species.

Model No.	Species	Ecological Variable	p-value	SRC	PCD	VIF
8	a	WI	0.000	0.192	0.083	1.147
		SR	0.000	-0.203	0.120	1.100
		RAIN	0.000	0.587	0.507	1.045
9	b	E	0.000	-0.463	0.252	1.647
		WI	0.038	0.096	0.018	1.278
		SR	0.005	-0.124	0.034	1.130
		RAIN	0.000	0.382	0.229	1.275
10	c	E	0.000	-0.480	0.262	1.057
		SR	0.012	-0.296	0.119	1.057
11	d	E	0.050	-0.178	0.051	1.294
		SD	0.005	-0.239	0.107	1.037
		RAIN	0.000	0.592	0.377	1.261

Species letters a,b,c,d correspond to the the following : a = *P. falcataria*, b = *E. peltatum*, c = *A. mangium*, d = *G. arborea;* SRC= Standard regression coefficients, PCD= partial coefficient of determination, VIF= variance inflation factor

resulting integrated models also have the highest R_a^2 and lowest SEE values indicating that these are the best-fit models for the target species. The regression statistics of the best-fit integrated models are given in Table 9.

Model 8, which is the best predictor model for *P. falcataria,* suggests that in the study area site index is limited by the ecological factors WI, SR, and RAIN. It can predict as much as 58% of the site index variation with SEE=1.256. In this model, RAIN has the greatest impact on site index (SRC=0.587) and the addition of this variable reduces the model sum of squares error by 51%.

In the case of *E. peltatum,* the best performing model (Model 9) includes E, WI, SR and RAIN variables. The model accountability is the highest among all species with R_a^2 =0.609 and SEE= 3.677. From among the ecological variables selected in the model, RAIN affects site index the most having an SRC value of 0.382 and can reduce SEE by as much as 23%.

Model 10, which is the best-fit model selected for *A. mangium,* comprised of E and SR as the most significant predictor variables. It can predict about 36% of the variation in site index and has an error of 3.615. Between the two variables, E has the higher SRC and PCD values, which is equal to 0.480 and 0.262, respectively.

Finally, Model 11 exhibited the highest values among all models tested for *G. arborea*. The independent variables selected in the model are E, SD, and RAIN, which in combination could take into account as much as 52% of site index variability with an error of 1.969. Similar to the results of the other three species, the variation in RAIN variable has the largest impact on site index with SRC = 0.592 and CPD=0.377.

The site index predicted values using the best-fit models for each species were generally in a 1:1 relationship with the measured site index values of the sample plots (Fig. 2). The selected models were further tested using data from the validation plots (Fig. 3). A bigger range of errors is observed for *E. peltatum* and *A. mangium* as compared to the other two species. The errors from the validation analysis are generally not biased and show no trend, but as expected, models performed better in the sample than in the validation plots. In the case of *G. arborea*, a slight

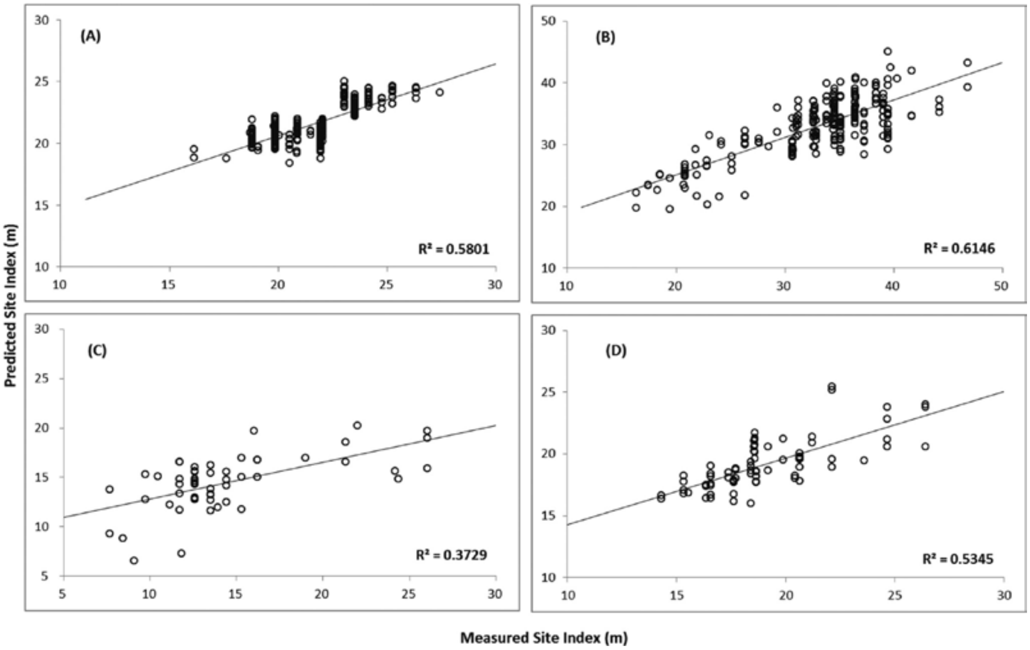

Fig. 2. Comparison of measured and predicted site index values for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using the best-fit integrated models

negative bias is observed but these may due to the limited distribution of validation plots for this species.

Site index mapping and site index variation

In order to determine the spatial distribution of site productivity in the study area, the selected predictor models resulting from the regression analysis were paired with weighted sum overlay analysis. The beta coefficients of the ecological variables in the regression models were used as weights in order to come up with raster maps showing the distribution of site productivity for the target species were developed. Figure 4 shows the range of site productivity supported by the study area with respect to the target tree species using the best fit model. Focusing on the production areas which correspond to the plantations, maps showing the mean estimated site index and its spatial variability across the plantation blocks were also developed. These maps were developed using the best-fit models (Fig.5).

Discussion

Regression analyses between site index and ecological factors were performed to model spatial variations in the site indices of four major industrial tree plantation species in the Philippines. The study also used the analytic approach to identify the main ecological factors affecting the variability of site index of the target species. Ten independent variables

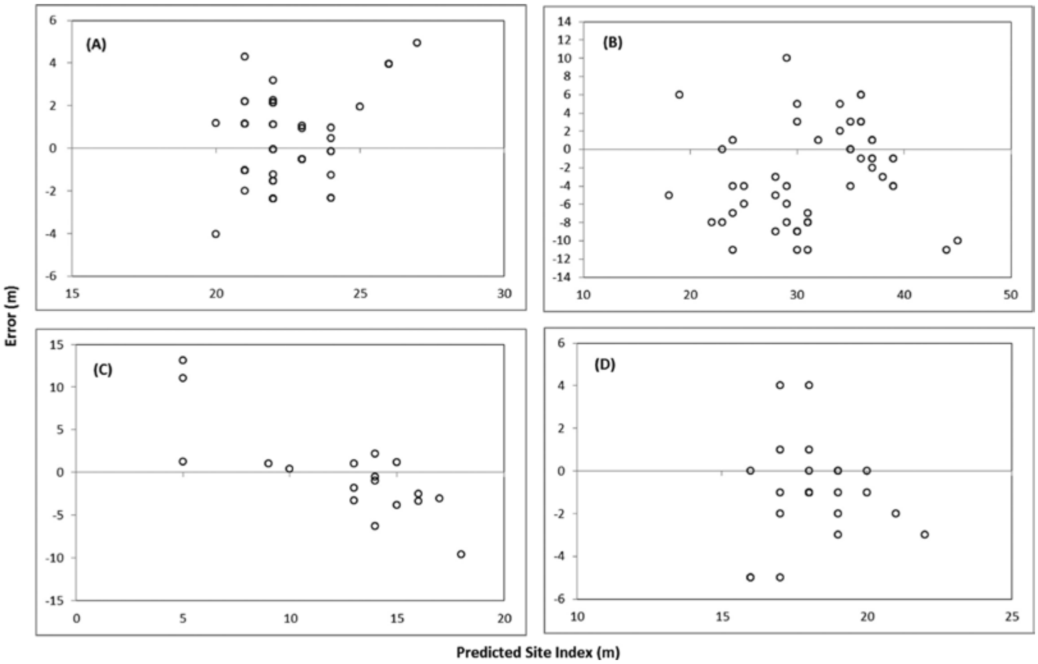

Fig. 3. Mean error from predicted site index on validation plots for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using the best-fit integrated models

grouped into four categories (topography, soil moisture, solar and wind and climate) and their combinations (integrated model) were tested. Studies relating ecological factors with site index of major plantation species are extremely scanty in the Philippines, so comparison of the results of the study were limited to the results of studies on other tree species.

Best species-specific site index predictor models

Among the four model groups tested for regression, climate models generally displayed the best prediction for *P. falcataria* and *A. mangium.* Adjusted R^2 values of the climate models for the two species are actually higher than the values reported in FARRELLY *et al.* (2011), FONTES *et al.* (2003), WANG and KLINKA (1996), ERCANLI *et al.* (2008), with values 0.28, 0.31, 0.02 and 0.295, respectively. The performance of the climate models for *E. peltatum* and *G. arborea* may be low relative to the two other species but the values are still higher than the values reported from above-mentioned studies. Topography models are commonly used in site-site index correlation studies and results of this study show that topography was able to model site index variation of *E. peltatum* by ~50%. These values are higher than the limits reported in MITSUDA *et al.* (2001) where topography models displayed a predictive power of 0.28-0.31 only. On the contrary, results obtained in the study are lower compared to the estimates of CHEN *et al.*, (1998) where elevation, aspect, and slope position factors predicted 60% of trembling aspen site index. In addition, studies of SEYNAVE *et al.* (2005), SOCHA (2008), and ERCANLI *et al.* (2008) reported higher performance of topography models, particularly elevation, explaining about 49-66% of

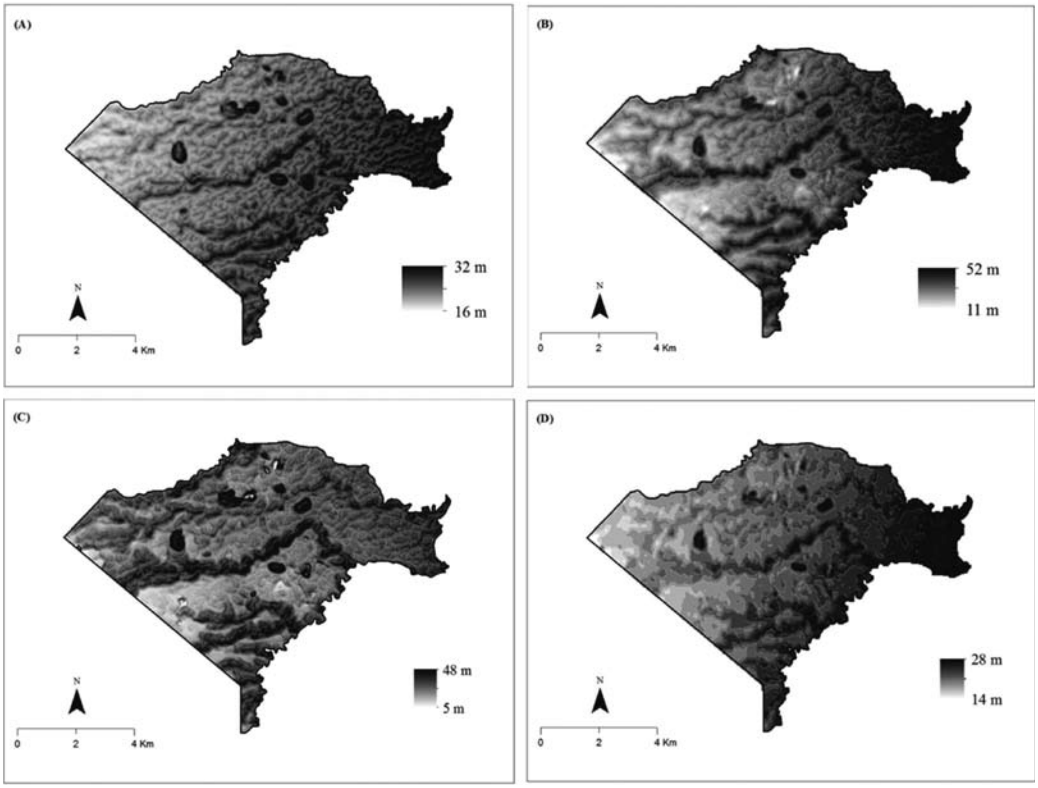

Fig. 4. Raster maps showing site index variability across the study area for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using the best-fit integrated models

variation in spruce site index. The differences in the performance of climate and topography models from this study compared with other studies may arise from species and geographic variation. The effects of topography and climate may be less or more pronounced depending on the species and geographic location.

Models related to soil moisture and exposure to sun and wind performed poorly (5-17%) in this study. This is relatively lower than the values reported in MITSUDA *et al.* (2007), which also used DEM-derived variables to model soil moisture and site exposure to sun and wind using different DEM resolutions. High predictive values range from 45-62 % using DEM scales 12.5 m and 50 m while low values using DEM with a resolution of 25 m and 100 m range from 15-31%. MITSUDA *et al.* (2007) and ZHANG and MONTGOMERY (1994) suggested that fine resolution DEM is necessary to model soil-water dynamics indicating that the coarse resolution of the map used in the study may have partly contributed to the poor performance of the models.

Main ecological factors affecting site productivity

Across the target species, best-fit models included different combinations of ecological variables. This indicates that site quality of plantation tree species is controlled not only by an

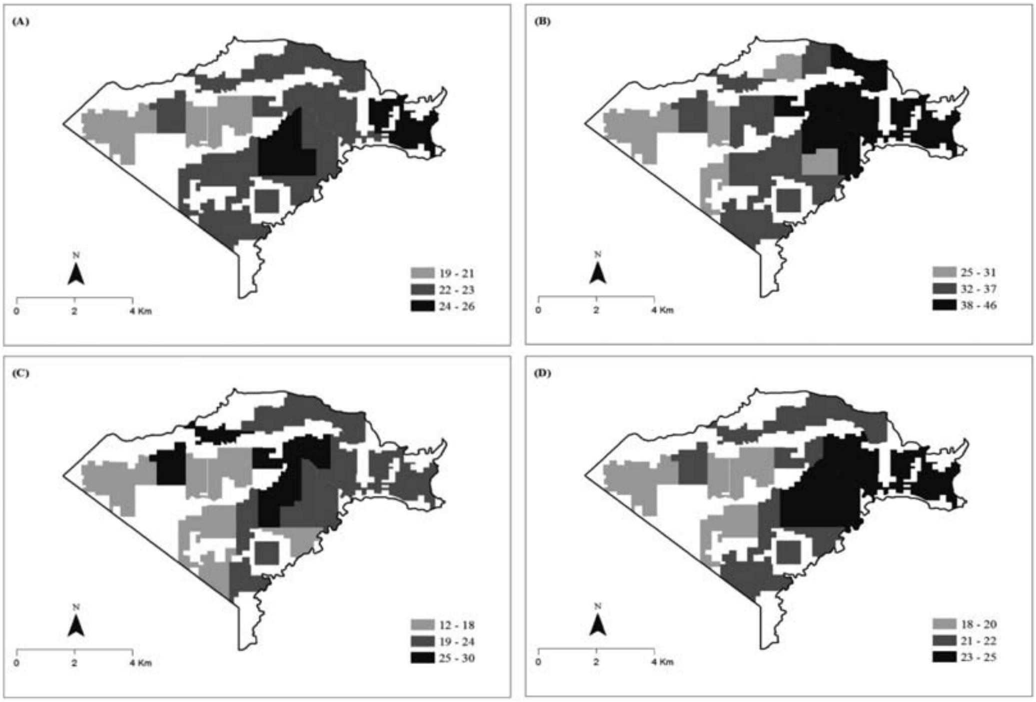

Fig. 5. Site index maps showing mean predicted site index and variability across the plantation areas (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using the best-fit integrated models

individual ecological factor but also by a combination of factors (ERCANLI *et al.*, 2008; CHEN and ABE, 1999). Based from the predictor model selected for *P. falcataria,* its site index is severely limited by the wetness index, exposure to direct solar radiation and amount of rainfall received by an area. Based on the results, *P. falcataria* prefers areas with high soil moisture located near valleys and river beds with lower exposure to direct sunlight and receives high amount of rainfall. Owing to the high evapo-transpiration nature of *P. falcataria* (KRISNAWATI *et al.*, 2011), its productivity decreases when high exposure to sun increases soil temperature and consequently increasing evapotranspiration. In the case of *E. peltatum*, variables elevation, wetness index, direct solar radiation and rainfall are greatly associated with site index variations. Higher productivity for this species could be achieved in areas with lower elevation and approaching water pathways. Growth is also perceived to be favorable in areas, which are not too exposed to sunlight and receives ample rainfall throughout the year. With regards to *A. mangium,* the limiting factors are site altitude and the amount of direct solar radiation. Site index is high in lower elevation and in areas with lower exposure to direct sunlight. The site index of *G. arborea* is limited by the following site factors: elevation, sunlight duration, and rain. High site productivity is expected from areas of lower elevation, which receives high amount of rainfall and with shorter sunlight exposure. A study of VANCLAY *et al.* (2008) in Leyte Province Philippines looked into the relationship between site index of *G. arborea* and the physical environment. The resulting model included soil depth and slope explaining about 15% of the site index variability. The predictor model developed in this study did not include slope as a significant predictor variable for *G. arborea* but it has a higher prediction power of 52%.

Spatially-referenced site index maps

The best-fit models give a numerical estimate of the area's site productivity but the developed raster maps give a visual idea of the probable distribution of the variation in site index. The full potential of species-specific site index models can be realized if it is combined with actual maps showing the ground location of areas with low and high site productivity. The maps show the variation of site index across the study area and the plantation areas for all species and variation appears to be at the highest with *E. peltatum and* lowest with *P. falcataria*. However, the site index variation for each species are not directly comparable with each other in the sense that a site index value of 50 for *E. peltatum* is not the same as the site index value of 50 for *P. falcataria* or other species. This is because they exhibit different growth patterns and site index were estimated using different base ages, for example site index for *P. falcataria* was estimated at base age 10 while a base age of 15 years was used for the site index estimated for *E. peltatum.*

Model scope and limitations

Several studies on modelling site index with site factors included soil and soil characteristics. These factors were not considered in the study. Soil variables were not included due to the following reasons (1) the objective is to model site index from easily measured and available ecological factors, and (2) the species targeted in the study are mostly well-adapted to a wide range of soil types and can grow well even on degraded sites. Although this study did not use soil and soil-related variables, the resulting models showed good predicting power using ecological factors other than soil. The performance of the models resulting from this study is comparable to the predicting power (23-81%) reported for models using soil variables (CARTER and KLINKA, 1990; WANG and KLINKA, 1996; CHEN *et al.*, 1998; CORONA *et al.*, 1998; CURT *et al.*, 2001; CHEN *et al.*, 2002; FONTES *et al.*, 2003; SEYNAVE *et al.*, 2005; LOUW and SCHOLES, 2006; ERCANLI *et al.*, 2008; SOCHA, 2008; FARRELLY *et al.*, 2011). Combining soil variables with the models used in the study may further improve the accountability of the developed species-specific models.

FARRELLY *et al.* (2011) stated that species-specific site index models to be useful must be able to explain at least 50% of the variation in site index. Best fit models for *P. falcataria, E. peltatum,* and *G. arborea* successfully meet this criterion except for *A. mangium* which missed the limit at 36%. In spite of the good performance exhibited by the best-fit models, still a portion of site index variation (39-64%) could not be explained by the models. Errors in site index estimation using ecological variables may be due to several reasons (CURT *et al.*, 2001; FONTES *et al.*, 2003; BOSELA *et al.*, 2013): (1) errors in sampling and field surveys, (2) non-inclusion of consistent descriptor of site index variation, (3) inadequate sampling of the ecological complexity of the study area, (4) genetic variation, (5) former land use and silviculture. In the case of the study, major possible sources of poor correlation may be genetic variation particularly for the introduced species and the failed attempt to model over-all complexity and variation of ecological factors using DEM data. The highly introduced species in the area, though well-adapted to a wide range of site characteristics, pose a problem when the provenances are not ascertained and determined. Another possible source of error is the limitation associated with the ecological factors considered in the study in particular the climatic variable rain. Model improvement could be achieved by the inclusion of samples covering a wide range of possible and more accurate values for each ecological factor. Moreover, using a finer-scale and resolution DEM data may help bring out a more truthful variation in the calculation of ecological variables used in the study. Moreover, the realibility of the site index estimates also depend on the site index equations used to determine measured site index values during model development. In order to increase accuracy of the models, the use of stem analysis method in determining site index of trees or stands for model development should also be explored.

Due to the limited scale from which this study was conducted, which is limited to only one study site, it may be difficult to provide a complete description of the site factors affecting the growth of the target species. However, the models substantially describe the factors affecting species productivity in the study area and in areas with similar characteristics where these species are intensively grown for commercial purposes. Studies relating site factors to site productivity are lacking in the Philippines and usually site quality estimation is anchored on results of small-scale species trials. The results of the study provide significant contribution in narrowing this knowledge gap and consequently in improving the management of industrial tree plantations.

Conclusion

In the Philippines, species-site matching is not appropriately implemented because of the severe lack of knowledge on spatial variation in site productivity of areas allocated for reforestation and plantation development. Knowledge of species-specific site productivity is important in forest management and the lack of it is usually one of the culprits behind failed reforestation attempts and poor growth and production in plantations. This study sought to address this problem by developing site index estimation models using ecological factors for major plantation species namely, *P. falcataria, E. peltatum, A. mangium,* and *G. arborea.* The highest model accountability was observed from the lone native species, *E. peltatum*, followed by *P. falcataria*, *G. arborea* and *A. mangium.* The best fit models selected for each species were able to explain as much as 36-61% of site index variation, making them fit for application in the study area. The models indicated that different site factors limit the productivity of each species, which justifies the importance of species-specific site index models.

The target species are described to be widely-adapted so it is possible that in other areas other ecological factors may be found significant for predicting their site indices. The results in this study were derived from a small-scale area and models could be further improved if values from a larger scale will be considered. The application of the models should be limited to the site and conditions considered in model development.

The results of the study provide baseline information on the site productivity of the study area where productivity was previously unknown and in estimating site index in areas where the target tree species trees are currently non-existent. These will serve as practical and valuable tools for forest managers by reducing the need for costly and time-consuming 'trial-and-error" methods in identifying what tree species are suitable to the site. They can also provide insight to help forest managers in making future decisions related to the sustainable management of forest plantations.

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Summary

The relationships between site index and ecological site factors were estimated to determine site productivity for *Paraserianthes falcataria, Endospermum peltatum, Acacia mangium* and G*melina arborea*, which are major industrial tree plantation species in Mindanao, Philippines. A digital elevation model was used to estimate the values of ecological factors and the site index was modeled using multiple linear regression analysis. Results of the study include integrated and common variable models that can be used to estimate the site index of each target tree species. Best-fit integrated models included variables such as elevation, wetness index, direct solar radiation, sunlight duration and amount of rainfall and were able to predict 36-61% of site index variability. In addition, the predictor models were combined with weighted overlay analysis to develop raster maps showing the spatial distribution of site index variability. The results of the study provided a means to estimate numerically and visually species-specific site indices, which are necessary to improve the management of forest plantations.

Keywords: Site index estimation, *Paraserianthes falcataria, Endospermum peltatum, Acacia mangium, Gmelina arborea*

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フィリピン ミンダナオ島における産業造林樹種の環境要因による地位指数の推定

アナリン　リコング　コディラン*[1,*2]・中島　徹*[1]・龍原　哲*[1]・白石則彦*[1]

＊1 東京大学大学院農学生命科学研究科森林科学専攻森林経理学研究室
＊2 フィリピン大学ロスバニョス校森林・天然資源学部再生可能天然資源研究所

要　旨

本研究は，フィリピン ミンダナオ島の主要な産業造林樹種である *Paraserianthes falcataria*, *Endospermum peltatum, Acacia mangium*, *Gmelina arborea* の土地生産力を判定するため，地位指数と環境要因との関係を推定した。環境要因の推定には数値標高モデルを用い，地位指数との関係を重回帰分析によってモデル化した。本研究の結果，対象樹種それぞれについて，地位指数を推定するための多変数および一変数モデルが得られた。最も適合した多変数モデルは，標高，湿性指数，日射量，日照時間および降水量を変数とし，地位指数のばらつきの36から61%を説明することができた。加えて，重回帰モデルと加重オーバーレイ解析とを組み合わせ，地位指数の空間分布を示すラスターマップを作成した。本研究によって，人工林経営の改善に役立つ樹種別の地位指数を定量的かつ視覚的に推定する手法を提示した。

キーワード：地位指数推定 · *Paraserianthes falcataria* · *Endospermum peltatum* · *Acacia mangium* · *Gmelina arborea*