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Comparison of stem taper models for the four tropical tree species in Mount Makiling, Philippines

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Abstract: This study was conducted to evaluate the performance of six stem taper models on four tropical tree species, namely *Celtis luzonica* (Magabuyo), *Diplodiscus paniculatus* (Balobo), *Parashorea malaanonan* (Bagtikan), and *Swietenia macrophylla* (Mahogany) in Mount Makiling Forest Reserve (MMFR), Philippines using fit statistics and lack-of-fit statistics. Four statistical criteria were used in this study, including the standard error of estimate (*SEE*), coefficient of determination (R^2), mean bias ($\overline{E}$), and absolute mean difference (*AMD*). For the lack-of-fit statistics, *SEE*, $\overline{E}$ and *AMD* were determined in different relative height classes. The results indicated that the Kozak02 stem taper model offered the best fit for the four tropical species in most statistics. The Kozak02 model also consistently provided the best performance in the lack-of-fit statistics with the best *SEE*, $\overline{E}$ and *AMD* in most of the relative height classes. These stem taper equations could help forest managers and researchers better estimate the diameter of the outside bark with any given height, merchantable stem volumes and total stem volumes of standing trees belonging to the four species of the tropical forest in MMFR.

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Introduction

The tropical forest in Mount Makiling Forest Reserve (MMFR), recently declared as among the ASEAN Heritage Park, is one of the best-known biological areas in the Philippines, basically due to its scientific history (Bantayan 2001). The forest reserve serves as natural training laboratory for the advancement of technical knowledge related to the conservation of the forest, its biodiversity and other resources (Pagaduan and Afuang 2012). Thus, it is considered to be a well-studied and well-researched ecosystem (Combalicer et al. 2010). Most of the previous studies conducted at MFR investigated carbon budgets (Lasco et al. 2004; Gevana and Pampolina 2007; Racelis et al. 2008;

Camacho et al. 2009), the impact of changes in land use (Bantayan 2001; Combalicer et al. 2011), climate change impact on water balance (Combalicer et al. 2010); species composition and microclimate (Lee et al. 2006); and conservation of the biodiversity of the flora and fauna (Bantayan et al. 2008; Pagaduan and Afuang 2012; Lapitan et al. 2013). However, no significant attempt has been made to date to develop the stem taper and volume equation, particularly for the most dominant species that thrive in the MMFR.

The importance of tropical forests has become more widely recognized due to their crucial role in mitigating climate change by acting as a carbon sink (Avitable et al. 2012) as well as the large emission associated with their disappearance (Houghton 2007). According to Angelsen (2009), an important international strategy to mitigate climate change involves reducing greenhouse gas (GHG) emissions resulting from deforestation and forest degradation in conjunction with conservation and enhancement of forest carbon stocks, in the form of sustainable forest management or REDD+, by providing incentives to developing nations to protect and sustainably manage forest resources with minimal changes in land use. In order to manage tropical forests in a sustainable manner, the estimates of the growing stock, such as volume biomass estimates, are required (Haywood 2009).

To make an estimate of the stem volume of standing trees, investigators usually measure the diameter of the tree at several heights up the trunk or, for species that are well studied, integrate mathematical taper functions (Philip 1994; Robinson and Wood 1994; Akindele and LeMay 2006). Subedi et al. (2011) recommended a stem taper equation as one of the most accurate tools to predict the stem diameter and the volume to any height of a standing tree. Taper equations provide information about how stem diameter changes as the height increases. Conversely, these equations can be used to estimate the height for a given stem diameter. The most common types of stem taper equation are the segmented polynomial taper model, such as the Max and Burkhart (1976) stem taper model that uses different sub-functions for various parts of the stem (Kozak 1988), and the variable exponent or form taper model, such as the Kozak (1988, 2004) and Lee et al. (2003) taper models that assume that the form of the tree changes continuously along the stem (Li et al. 2012). According to Kozak (2004), stem taper equations are better than volume equations since the taper equations can provide estimates of the diameter at any point along the stem, merchantable height to any top diameter and from any stump height, and the volume of a stem log at any length and at any height from ground, aside from the merchantable stem volume and the total stem volume estimation. On the other hand, volume equations can only estimate the merchantable and the total stem volume of standing trees (Kozak 2004).

Since cutting or harvesting trees is strictly prohibited in the study site because it is located within a forest reserve, the aim of this study was to develop stem taper models without felling trees and without causing indelible damage to the tree or to the nearby understory. The scope of study involves four dominant tree species in the MFR (Fernando et al. 2008; Lapitan et al. 2010): *Celtis luzonica* Warb. (Magabuyo), *Diplodiscus paniculatus* Turez. (Balobo) and *Parashorea malaanonan* (Blanco) Merr. (Bagtikan), as well as *Swietenia macrophylla* King (Big Leaf Mahogany).

1 Materials and Methods

1.1 Study site

This study was conducted at the Permanent Field Laboratory Area at MMFR in the south-central region of Luzon Island, the Philippines and is located 65 km southeast of Metro Manila (Figure 1). Most of the original vegetation that formed at the base of the mountain had been selectively logged from 1942 to 1944 (Luna et al. 1999). Therefore, the current vegetation belongs to a secondary tropical rainforest, and no specific anthropogenic disturbance has been reported since then. The forest reserve is composed of four vegetation types: the mossy forest zone (900 to 1109 m asl), the dipterocarp mid-montane forest zone (100 to 900 m asl), the grass-land zone, and the agroforestry zone (Gruezo 1997). The data collection was conducted in the areas with less than 140 m asl. The dry season for this area lasts from January to April, and the wet season lasts from

May to December. The mean annual rainfall ranged from 1645 to 2299 mm, and the mean annual temperature ranged from 25.90°C to 29.30°C, as recorded at the nearest national weather station for the past five years (2005-2010).

Ecologically, tropical trees growing in volcanic rich-soil had mean annual increments in diameter and height of 0.81 cm and 0.78 m yearly, respectively. This was exemplified by growth of native *Parashorea malaanonan*, *Diplodiscus paniculatus*, and was higher than exotic *Swietenia macrophylla* (Schnieder et al. 2014). *Celtis luzonica* which favorably grow on the same ecosystem and soil type would probably showed similar growth rate, though distribution and habitat are under threat (Garcia et al. 2013).

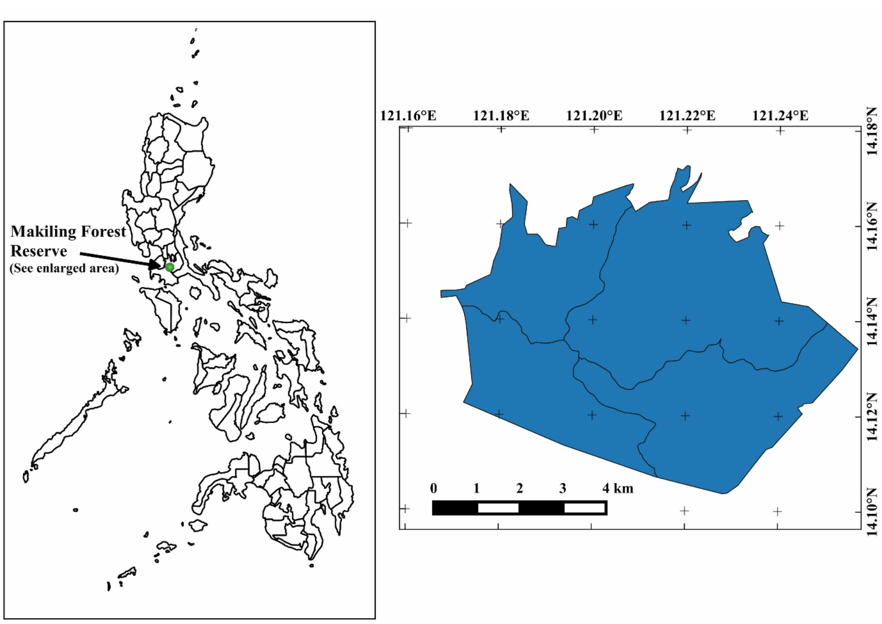

Figure 1 Geographic location of Mt. Makiling Forest Reserve, Philippines.

1.2 Data collection

A total of 200 trees representing different diameter at breast height (DBH) classes and total height classes were measured for each of the species. DBH was measured at 1.30 m from the ground using a standard diameter tape, and the total height was measured using a Haglof Vertex III and Transponder. For trees with buttress, height from the ground and diameter were measured 30 cm above the top of the buttress. The diameter of the outside bark (DOB, cm) along the stem and the height from the ground (m) was measured using a Criterion RD1000 instrument. The DOBs along the stem of each tree were measured starting from 30 cm above the ground at intervals of 1-2 m. A summary of the data that was collected is shown in Table 1.

1.3 Data analysis

The stem taper models published by Kozak in 1988 (Kozak88) and in 2004 (Kozak01 and Kozak02) and the stem taper model published by Max and Burkhart (1976; MB76) are commonly used stem taper equations and were selected as candidate models to estimate the DOB at any given height of the four tropical tree species in MFR. In addition, the model developed by Lee et al. (2003; Lee03) for *Pinus densiflora* in Korea and a modification of the Lee03 model (Mod Lee03) made by Berhe and Arnoldsson (2008) for *Cupressus lusitanica* plantations in Ethiopia were

Table 1 Summary of the observed statistics used as data to develop the stem taper models for the four tropical species in Mt. Makiling Forest Reserves, Philippines

Species	Variable	*n*	Mean	Min.	Max.	SD
Celtis luzonica	Total height	200	14.19	5.00	30.70	5.88
	Diameter at breast height	200	20.46	5.00	70.60	16.65
Diplodiscus paniculatus	Total height	200	16.19	4.60	32.40	5.32
	Diameter at breast height	200	26.25	5.20	81.70	15.44
Parashorea malaanonan	Total height	200	23.28	6.20	43.00	10.38
	Diameter at breast height	200	34.37	5.20	97.40	23.73
Swietenia macrophylla	Total height	200	23.90	6.70	36.70	6.59
	Diameter at breast height	200	53.88	6.10	132.10	24.68

also used for stem taper development and evaluation. These equations were selected since they provided better estimates for DOB at any given height for various species in many countries (Figueiredo-Filho et al. 1996; Brooks et al. 2002; Lee et al. 2003; Kozak 2004; Jiang et al. 2005; Rojo et al. 2005; Coble and Hilpp 2006; Corral-Rivas et al. 2007; Klos et al. 2007; Berhe and Arnoldsson 2008; Brooks et al. 2008; Son et al. 2009; Li and Weiskittel 2010; Heidarsson and Pukkala 2011; Li et al. 2012).

The Statistical Analysis System Non-linear (SAS NLIN) procedure was used to estimate the parameters of these models (SAS Institute Inc. 2004), and the mathematical forms of the six stem taper models are shown in Table 2.

1.4 Data Evaluation

The performance of the six stem taper models was evaluated by calculating the standard error of estimate (*SEE*), coefficient of determination (R^2), bias ($\overline{E}$), and absolute mean difference (*AMD*). These statistical criteria were computed as follows:

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(d_i - \hat{d}_i)^2}{n-k}}$$

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{n}(d_i - \hat{d}_i)^2}{\sum_{i=1}^{n}(d_i - \overline{d})^2}\right]$$

$$\overline{E} = \frac{\sum_{i=1}^{n}(d_i - \hat{d}_i)}{n}$$

$$AMD = \frac{\sum_{i=1}^{n}\left|d_i - \hat{d}_i\right|}{n}$$

where: d_i = observed variable,
$\hat{d}_i$ = predicted variable,
$\overline{d}$ = observed mean of the variable,
n = number of observation,
k = number of model parameters.

2 Results and Discussion

The parameters for the six candidate models (Kozak88, Kozak01, Kozak02, MB76, Lee03 and

Table 2 Six stem taper equations selected as candidate models for four tropical species in Mt. Makiling Forest Reserves, Philippines

Model	Mathematical form [1]	Reference
Kozak88	$\hat{d} = a_1 D^{a_2} a_3{}^D X^{b_1 Z^2 + b_2 \ln(Z+0.001) + b_3 Z^{1/2} + b_4 e^Z + b_5 (D/H)}$ where: $X = \frac{(1-Z^{1/2})}{(1-p^{1/2})}$, p = proportional height of the "inflection point"	Kozak 1988
Kozak01	$\hat{d} = a_1 D^{a_2} X^{b_1 + b_2(1/e^{D/H}) + b_3 D^X + b_4 X^{D/H}}$ where: $X = \frac{(1-Z^{1/4})}{(1-0.010^{1/4})}$	Kozak 2004
Kozak02	$\hat{d} = a_1 D^{a_2} H^{a_3} X^{b_1 Z^4 + b_2(1/e^{D/H}) + b_3 X^{0.100} + b_4(1/D) + b_5 H^Q + b_6 X}$ where: $Q = (1-Z^{1/3})$, $X = \frac{Q}{(1-(1.3/H)^{1/3})}$	Kozak 2004
MB76	$\frac{\hat{d}^2}{D^2} = b_1(Z-1) + b_2(Z^2-1) + b_3(a_1-Z)^2 I_1 + b_4(a_2-Z)^2 I_2$ where: $I_i = \begin{cases} 1, & if \quad Z \le a_i \\ 0, & if \quad Z > a_i \end{cases} \quad i = 1,2$	Max and Burkhart 1976
Lee03	$\hat{d} = a_1 D^{a_2}(1-Z)^{b_1 Z^2 + b_2 Z + b_3}$	Lee et al. 2003
Mod Lee03	$\hat{d} = a_1 D^{a_2}(1-\sqrt{Z})^{b_1 Z^2 + b_2 Z + b_3}$	Berhe and Arnoldsson 2008

Notes: [1]*D* is DBH (cm), *H* is the tree total height (m), *h* is the height from the ground (m), *Z* is proportional height from the ground (*h* /*H*), $\hat{d}$ is the predicted diameter outside bark at a height from the ground *h* (cm), and a_i, b_i are the estimated parameters.

Table 3 Estimated parameter for the six candidate stem taper models for the four tropical species in Mt. Makiling Forest Reserves, Philippines

Species	Model	a_1	a_2	a_3	b_1	b_2	b_3	b_4	b_5	b_6
Celtis luzonica	Kozak88	1.2271	0.9817	1.0001	2.4156	-0.9051	5.3547	-2.7992	-0.0665	
	Kozak01	1.4034	0.9329		0.0999	0.3550	-0.0015	0.1767		
	Kozak02	1.0194	0.9785	0.0271	0.1005	0.7110	0.0481	-0.9816	-0.0109	0.1402
	MB76	0.8193	0.0824		18.1292	-11.5266	11.3938	58.8754		
	Lee03	1.0232	1.0129		0.8435	-1.3177	0.7483			
	Mod Lee03	1.0867	1.0142		0.3528	-0.5420	0.4047			
Diplodiscus paniculatus	Kozak88	1.0410	1.0408	0.9987	2.3995	-0.8585	5.0247	-2.6680	-0.0445	
	Kozak01	1.2983	0.9584		0.0810	0.4584	0.0068	0.0715		
	Kozak02	1.0426	0.9768	0.0219	0.0130	0.6819	0.0345	-0.1682	-0.0053	0.0923
	MB76	0.6376	0.8737		106.9000	-60.6445	-1.5258	62.9045		
	Lee03	0.9686	1.0256		0.2310	-0.7822	0.6046			
	Mod Lee03	1.0139	1.0262		-0.0413	-0.1939	0.2980			
Parashorea malaanonan	Kozak88	1.0338	1.0302	0.9991	1.3935	-0.6020	3.5771	-1.6969	-0.1224	
	Kozak01	1.2032	0.9689		0.0331	0.8513	0.0062	-0.2194		
	Kozak02	0.9485	0.9642	0.0623	-0.0478	0.9927	0.0779	-1.1581	0.0020	-0.0949
	MB76	0.8389	0.0458		21.8510	-13.4302	13.4711	149.8000		
	Lee03	0.8339	1.0573		0.2354	-0.6531	0.6179			
	Mod Lee03	0.8674	1.0588		0.0242	-0.1426	0.2982			
Swietenia macrophylla	Kozak88	1.2039	0.9882	1.0000	2.2190	-0.8584	5.1746	-2.6634	-0.0469	
	Kozak01	1.3371	0.9560		0.1270	0.6515	0.0043	0.0898		
	Kozak02	1.0501	0.9794	0.0188	0.0089	0.8468	0.0984	0.2160	0.0201	-0.0729
	MB76	0.6974	0.0621		7.3161	-5.5133	5.8596	91.4181		
	Lee03	0.9586	1.0243		1.0049	-1.5115	0.8333			
	Mod Lee03	1.0092	1.0252		0.2945	-0.4688	0.3928			

Mod Lee03) were estimated and are shown in Table 3. The four fit statistics (*SEE*, R^2, $\overline{E}$ and *AMD*) were used to evaluate the performance of these models and are ranked as shown in Table 4. The model evaluation and rank analysis revealed that the Kozak02 had the best performance for *Celtis luzonica*, with the best *SEE* (0.7142), R^2 (0.9992), and *AMD* (0.4750) while Lee03 offered the poorest performance (*SEE*: 1.0342, R^2: 0.9983, and *AMD*: 0.7210 cm). For *Diplodiscus paniculatus*, Kozak02 also had the best rank, with the best *SEE* (0.8204), R^2 (0.9992), and *AMD* (0.5510). Kozak02 was also superior among the candidate models for *Parashorea malaanonan* (*SEE*: 2.1100, R^2: 0.9969, $\overline{E}$: -0.0120 and *AMD*: 1.2900) and *Swietenia macrophylla* (*SEE*: 1.2082, R^2: 0.9995, $\overline{E}$: 0.0180 and *AMD*: 0.8650). The other models developed by Kozak (Kozak88, Kozak01) also exhibited better performance relative to the other models for all tropical species in this study.

Lack-of-fit statistics were used instead of model validation to further evaluate the performance of the different candidate stem taper models because model validation could provide little information with respect to the model evaluation process. In lack-of-fit statistics, evaluation statistics are determined in various subgroups of the independent variable. In this study, *SEE*, $\overline{E}$ and *AMD* in different relative height classes (with 0.1 intervals) were determined to select the most suitable model. Furthermore, the rank analysis procedure suggested by Berhe and Arnoldsson (2008) was used for each of the tropical species. Rank one was given to the best model and rank six was given to the poorest model for each of the evaluation statistics (*SEE*, $\overline{E}$ and *AMD*) and for every relative height class. The results showed that the Kozak02 model offered the best performance in terms of most of the relative height classes for *Celtis luzonica* (Table 5), *Diplodiscus paniculatus* (Table 6), *Parashorea malaanonan* (Table 7), and *Swietenia macrophylla* (Table 8). This model was followed by the Kozak88 model for *Celtis luzonica* and *Parashorea malaanonan* and the Kozak01 model for *Diplodiscus paniculatus* and *Swietenia macrophylla*. On the other hand, the MB76 model provided the poorest performance among the candidate models for four of the tropical species.

Table 4 Evaluation statistics for different fitted stem taper models for the four tropical species in Mt. Makiling Forest Reserves, Philippines

Species	Model	*SEE*	R^2	$\overline{E}$	*AMD*	Rank
Celtis luzonica	Kozak88	0.7639	0.9991	0.0010	0.5040	2
	Kozak01	0.7463	0.9991	0.0470	0.4910	3
	Kozak02	0.7142	0.9992	-0.0030	0.4750	1
	MB76	1.0093	0.9984	-0.1480	0.6690	4
	Lee03	1.0342	0.9983	0.0280	0.7210	6
	Mod Lee03	1.0131	0.9983	0.0300	0.7080	5
Diplodiscus paniculatus	Kozak88	0.9765	0.9989	0.0000	0.6310	2
	Kozak01	0.8552	0.9991	0.0330	0.5740	3
	Kozak02	0.8204	0.9992	0.0020	0.5510	1
	MB76	1.3238	0.9979	-0.1490	0.9310	6
	Lee03	1.2764	0.9980	0.0060	0.8920	5
	Mod Lee03	1.2606	0.9981	0.0050	0.8860	4
Parashorea malaanonan	Kozak88	2.1322	0.9968	0.0160	1.3260	2
	Kozak01	2.1132	0.9969	0.0560	1.3620	2
	Kozak02	2.1100	0.9969	-0.0120	1.2900	1
	MB76	2.8658	0.9942	-0.7620	1.8280	6
	Lee03	2.7000	0.9949	0.0600	1.8100	5
	Mod Lee03	2.6820	0.9949	0.0640	1.8000	4
Swietenia macrophylla	Kozak88	1.3489	0.9994	-0.0120	0.9300	2
	Kozak01	1.2493	0.9995	0.0430	0.8930	3
	Kozak02	1.2082	0.9995	0.0180	0.8650	1
	MB76	1.9271	0.9988	-0.3380	1.3160	4
	Lee03	1.9878	0.9987	0.0220	1.4040	6
	Mod Lee03	1.9406	0.9988	0.0220	1.3800	4

Table 5 Lack-of-fit statistics for the six candidate models in the different relative height classes for *Celtis luzonica* in Mt. Makiling Forest Reserve, Philippines

Statistics	Relative height	Kozak88	Kozak01	Kozak02	MB76	Lee03	Mod Lee03
SEE	<0.1	1.04	1.05	1.04	1.22	1.53	1.46
	0.1-0.2	0.37	0.39	0.37	0.46	0.50	0.49
	0.2-0.3	0.57	0.57	0.53	0.76	0.70	0.70
	0.3-0.4	0.74	0.69	0.65	1.04	0.97	0.95
	0.4-0.5	0.87	0.75	0.78	1.11	1.04	1.04
	0.5-0.6	0.90	0.85	0.82	1.27	1.19	1.18
	0.6-0.7	0.88	0.97	0.85	1.36	1.21	1.21
	>0.7	1.34	1.24	1.06	1.97	1.71	1.73
AMD	<0.1	0.59	0.66	0.64	0.78	1.14	1.06
	0.1-0.2	0.21	0.25	0.28	0.30	0.38	0.39
	0.2-0.3	0.40	0.39	0.37	0.52	0.51	0.52
	0.3-0.4	0.54	0.48	0.46	0.73	0.69	0.68
	0.4-0.5	0.63	0.52	0.53	0.82	0.76	0.76
	0.5-0.6	0.68	0.61	0.57	0.92	0.86	0.86
	0.6-0.7	0.66	0.70	0.61	0.80	0.79	0.78
	>0.7	0.76	0.84	0.54	1.04	1.05	1.05
$\overline{E}$	<0.1	0.12	0.06	0.00	0.27	0.63	0.52
	0.1-0.2	0.04	0.01	-0.07	-0.09	0.01	0.12
	0.2-0.3	-0.01	0.11	0.09	-0.26	0.09	0.13
	0.3-0.4	-0.10	0.02	0.01	-0.33	-0.04	-0.07
	0.4-0.5	-0.06	-0.02	-0.05	-0.34	-0.27	-0.30
	0.5-0.6	-0.01	-0.03	-0.06	-0.24	-0.42	-0.40
	0.6-0.7	0.15	0.26	0.14	-0.01	-0.23	-0.17
	>0.7	0.02	0.51	0.37	0.27	0.10	0.16
Sum		59	60	41	121	111	112
Overall rank		2	3	1	6	4	5

Table 6 Lack-of-fit statistics for the six candidate models in the different relative height classes for *Diplodiscus paniculatus* in Mt. Makiling Forest Reserve, Philippines

Statistics	Relative height	Kozak88	Kozak01	Kozak02	MB76	Lee03	Mod Lee03
SEE	<0.1	1.44	1.30	1.29	1.76	1.93	1.87
	0.1-0.2	0.52	0.54	0.48	0.93	0.67	0.65
	0.2-0.3	0.74	0.68	0.65	1.05	0.87	0.88
	0.3-0.4	0.91	0.74	0.72	1.31	1.13	1.13
	0.4-0.5	1.08	0.86	0.83	1.63	1.43	1.43
	0.5-0.6	0.86	0.65	0.68	1.25	1.10	1.10
	0.6-0.7	1.16	0.81	0.89	1.95	1.68	1.66
	>0.7	3.51	2.82	3.41	1.38	1.52	1.76
AMD	<0.1	0.89	0.88	0.90	1.34	1.35	1.31
	0.1-0.2	0.33	0.36	0.32	0.70	0.49	0.49
	0.2-0.3	0.49	0.47	0.44	0.79	0.65	0.66
	0.3-0.4	0.62	0.51	0.49	1.01	0.82	0.82
	0.4-0.5	0.76	0.60	0.58	1.27	1.07	1.07
	0.5-0.6	0.86	0.71	0.70	1.42	1.19	1.19
	0.6-0.7	0.72	0.63	0.63	1.43	1.21	1.19
	>0.7	1.11	1.43	0.66	0.76	0.97	1.12
$\overline{E}$	<0.1	0.29	0.17	-0.01	0.21	0.69	0.58
	0.1-0.2	0.08	0.01	-0.10	-0.64	-0.05	0.03
	0.2-0.3	-0.04	0.08	0.11	-0.52	0.08	0.12
	0.3-0.4	-0.17	-0.01	0.08	-0.55	-0.03	-0.05
	0.4-0.5	-0.15	-0.10	-0.04	-0.70	-0.31	-0.35
	0.5-0.6	-0.05	-0.09	-0.12	-0.84	-0.56	-0.58
	0.6-0.7	0.01	0.26	0.12	-0.99	-0.76	-0.73
	>0.7	0.57	1.43	0.60	-0.11	0.48	0.67
Sum		71	56	49	124	103	101
Overall rank		3	2	1	6	5	4

Table 7 Lack-of-fit statistics for the six candidate models in the different relative height classes for *Parashorea malaanonan* in Mt. Makiling Forest Reserve, Philippines

Statistics	Relative height	Kozak88	Kozak01	Kozak02	MB76	Lee03	Mod Lee03
SEE	<0.1	1.09	1.14	1.19	1.17	2.10	1.99
	0.1-0.2	0.87	1.01	0.94	1.13	1.15	1.14
	0.2-0.3	1.31	1.49	1.58	1.88	1.54	1.55
	0.3-0.4	1.84	1.78	1.80	2.60	2.17	2.16
	0.4-0.5	2.39	2.29	2.30	3.35	2.89	2.88
	0.5-0.6	3.19	3.10	3.11	4.12	3.78	3.77
	0.6-0.7	3.82	3.65	3.65	5.02	4.67	4.66
	>0.7	5.14	4.97	5.06	6.84	6.51	6.52
AMD	<0.1	0.66	0.74	0.75	0.75	1.59	1.52
	0.1-0.2	0.61	0.67	0.56	0.77	0.97	0.99
	0.2-0.3	0.92	0.99	0.95	1.37	1.21	1.22
	0.3-0.4	1.28	1.26	1.20	1.91	1.59	1.59
	0.4-0.5	1.65	1.63	1.56	2.48	2.04	2.03
	0.5-0.6	2.21	2.25	2.14	2.92	2.61	2.60
	0.6-0.7	2.69	2.70	2.54	3.53	3.25	3.24
	>0.7	3.56	3.60	3.41	4.84	4.69	4.67
$\overline{E}$	<0.1	0.02	-0.10	-0.10	-0.23	0.81	0.66
	0.1-0.2	0.17	0.01	-0.01	-0.50	0.25	0.42
	0.2-0.3	0.03	0.14	0.14	-0.79	0.22	0.32
	0.3-0.4	-0.14	0.02	-0.02	-0.99	0.04	0.04
	0.4-0.5	-0.22	-0.08	-0.17	-1.26	-0.38	-0.43
	0.5-0.6	0.13	0.14	-0.01	-0.91	-0.40	-0.44
	0.6-0.7	0.21	0.32	0.07	-0.98	-0.76	-0.73
	>0.7	0.00	0.60	0.17	-0.29	-0.44	-0.29
Sum		52	53	48	130	115	106
Overall rank		2	3	1	6	5	4

Table 8 Lack-of-fit statistics for the six candidate models in the different relative height classes for *Swietenia macrophylla* in Mt. Makiling Forest Reserve, Philippines

Statistics	Relative height	Kozak88	Kozak01	Kozak02	MB76	Lee03	Mod Lee03
SEE	<0.1	1.66	1.63	1.63	1.78	2.56	2.38
	0.1-0.2	0.80	0.82	0.79	0.98	0.97	0.98
	0.2-0.3	1.12	1.05	1.00	1.65	1.51	1.50
	0.3-0.4	1.32	1.19	1.12	2.16	1.96	1.96
	0.4-0.5	1.70	1.46	1.39	2.80	2.56	2.55
	0.5-0.6	1.93	1.52	1.51	3.00	2.83	2.81
	>0.6	2.97	2.10	2.20	3.91	3.72	3.76
AMD	<0.1	1.07	1.19	1.23	1.19	1.89	1.77
	0.1-0.2	0.53	0.55	0.52	0.67	0.72	0.74
	0.2-0.3	0.79	0.75	0.70	1.17	1.12	1.12
	0.3-0.4	1.01	0.90	0.84	1.63	1.46	1.45
	0.4-0.5	1.30	1.11	1.05	2.06	1.89	1.89
	0.5-0.6	1.44	1.14	1.09	2.11	2.03	2.02
	>0.6	1.54	1.39	1.36	2.21	2.25	2.27
$\overline{E}$	<0.1	0.11	-0.05	-0.16	0.06	0.45	0.33
	0.1-0.2	0.15	0.17	0.15	-0.18	0.07	0.27
	0.2-0.3	-0.04	0.12	0.15	-0.42	0.20	0.19
	0.3-0.4	-0.15	-0.11	-0.09	-0.67	-0.23	-0.33
	0.4-0.5	-0.09	-0.08	-0.14	-0.63	-0.56	-0.58
	0.5-0.6	0.15	0.23	0.16	-0.57	-0.61	-0.48
	>0.6	-0.16	0.49	0.30	0.27	0.63	0.77
Sum		52	45	37	107	101	99
Overall rank		3	2	1	6	5	4

This evaluation method is important because a single overall value from the fit statistics may not indicate which model best predicts the DOB at any given height (Kozak and Smith 1993; Kozak and Kozak 2003). With respect to bias, the negative and positive biases in the different parts of the stem better overall bias while the model fails to fit well in some other portion of the tree (Berhe and Arnoldsson 2008).

The superiority of the Kozak02 model was consistent with the observations made in previous stem taper studies. A comprehensive stem taper study conducted by Kozak (2004) evaluated the four models he developed, and the results showed that the Kozak02 model was best in predicting the DOB at any given height based on 38 species groups consisting of 53,603 trees. Rojo et al. (2005) conducted a study in Galicia, Northwestern Spain to evaluate the performance of 31 stem taper equations on *Pinus pinaster*. The MB76 stem taper model was considered to be the best segmented model whereas the Kozak88 model and Kozak02 model were considered to be the two best variable-form models. The results of further evaluation and validation showed that the Kozak02 model was the recommended stem taper model for *Pinus pinaster*. Furthermore, the Kozak02 model was also chosen as the best stem taper model to predict the DOB of *Pinus contorta* and *Larix sibirica* in Iceland (Heidarsson and Pukkala 2011) and *Cupressus lusitanica* in Ethiopia (Berhe and Arnoldsson 2008). Moreover, among the 10 stem taper models that were developed for *Picea rubens* and *Pinus strobus*, Kozak02 was the most accurate model in predicting DOB (Li and Weiskittel 2010). Furthermore, Kozak02 was selected for the development of stem taper model for 11 conifer species in the Acadian Region, north America (Li et al. 2012) and *Betula pubescens* in northwestern Spain (Gomez-Garcia 2013).

Fit statistics and lack-of-fit statistics revealed that Mod Lee03 performed better when estimating DOB than the original Lee03 model. This result is consistent with a study by Berhe and Arnoldsson (2008) that showed that Mod Lee03 ranked third next to Kozak02 and Kozak88 and performed better than Lee03 in estimating the DOB at any given height for *Cupressus lusitanica*.

This study establishes that DBH and the total height data can be applied to predict the stem profile or DOB at any given height for the four tropical species by using the Kozak02 model, which is the best model in this study, as shown in Figure 2. Another significant application of the stem taper model is in the stem volume estimation of these species. Li et al. (2012) suggested two steps to predict the volume of a tree using a stem taper model: prediction of the DOB in the different height positions using the best model (Kozak02 model) by substituting the estimated parameters as well as volume estimation of the different log sections using Smalian's formula. For instance, the total volume of a *Celtis luzonica* sample with a DBH of 20 cm and a total height of 14 m must be estimated.

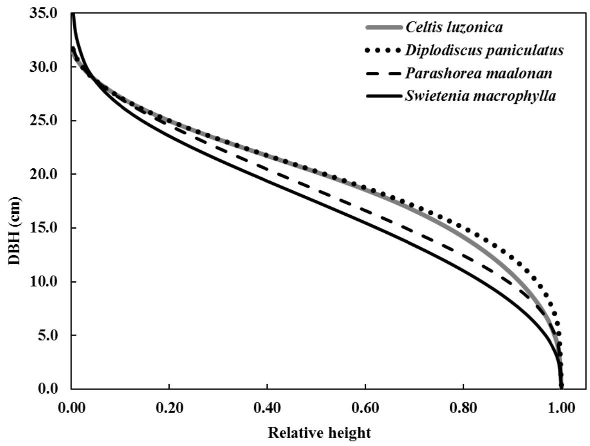

Figure 2 Stem profiles of the four tropical species in Mt. Makiling Forest Reserve, Philippines predicted using Kozak02, the best stem taper model of this study. Diameter at breast height (DBH) is 28 cm and total height is 30 m.

The DOBs starting from a stump height of 0.30 from the ground up until the total height, with intervals of 0.50 m, can be determined as follows:

$Z_1 = 0.30/14 = 0.02$,

$Q_1 = (1\text{-}0.02^{1/3}) = 0.72$

$X_1 = 0.72/[1\text{-}(1.3/14)^{1/3}] = 1.32$,

$$d_1 = 1.0194 \times 20^{0.9785} \times 14^{0.0271} \times 1.32^{\{[0.1005\times 0.02^4]+[0.7110(1/e^{20/14})]+[0.0481\times 1.32^{0.1}]+[-0.9816\times(1/20)]+[-0.0109\times 14^{0.72}]+[0.1402\times 1.32]\}}$$

$d_1 = 22.21$ cm

The DOB for the next height position (h_2 = 0.80 m) can also be determined as follows:

$Z_2 = 0.80/14 = 0.06$,

$Q_2 = (1\text{-}0.06^{1/3}) = 0.61$

$X_2 = 0.61/[1\text{-}(1.3/14)^{1/3}] = 1.12$,

$$d_2 = 1.0194 \times 20^{0.9785} \times 14^{0.0271} \times 1.12^{\{[0.1005\times 0.06^4]+[0.7110(1/e^{20/14})]+[0.0481\times 1.12^{0.1}]+[-0.9816\times(1/20)]+[-0.0109\times 14^{0.61}]+[0.1402\times 1.12]\}}$$

$d_2 = 21.20$ cm

This process can be performed at every 0.5 m interval in height until a height of 13.8 m. The volume for each section can now be determined using Smalian's formula, as shown below:

$V_1 = 0.00007854 \times [(d_1^2 + d_2^2)/2] \times$ Length of the log

$V_1 = 0.00007854 \times [(22.21^2 + 21.20^2)/2] \times 0.5$

$V_1 = 0.0185$ m^3

The volumes from the different sections can then be summed to obtain a total volume of this tree of 0.2924 m^3. This procedure can also be used to determine the stem volume of the tree or for any section of log volume. A spreadsheet or some other computer program is recommended for use in this calculation since it is relatively easier than using a pocket calculator (Li et al. 2012).

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