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Journal of Forest Planning is a peer-reviewed periodical that publishes articles, reviews, and short communications. It covers all aspects of forest management, modeling, and assessment such as forest inventory, growth and yield modeling, remote sensing and geospatial information technologies for forest management, forest management planning, forest zoning, evaluation of ecosystem services, managerial economics, and silvicultural systems. Manuscripts regarding forest policy, forest economics, forest environmental education, landscape management, climate change mitigation and adaptation strategies, and drone applications for forest management are welcome. The Journal aims to provide a forum for international communication among forest researchers and forestry practitioners who are interested in the above-mentioned fields.

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Comparative Study on Commercial Log Production Managed under Different Conditions: Evaluating Plantation Grown Teak of Sri Lanka

Pavithra Rangani Wijenayake [1,*], Takuya Hiroshima [2] and Hirokazu Yamamoto [3]

ABSTRACT

Several methods are available to assess the plantation timber volume at their maturity. However, most of those methods can not be applied to the teak (*Tectona grandis* L.f) plantations of Sri Lanka, due to different site qualities and different management practices since planting. Therefore it is essential to carry out a comparative study of commercial log production managed under different conditions. For this purpose, the use of height-diameter and relative taper curves for estimation and prediction of planted teak stands in dry and intermediate zones of Sri Lanka were evaluated. Even-age mature plantations which are subjected to clear fell was selected randomly. Standing tree measurements of 164 trees were taken at three sites to build up the height-diameter curve. At the same time, 158 trees were felled and took diameter measurements along the felled log to construct the relative taper curve. The resulted models are useful in generating accurate and localized predictions of standing tree height, total timber volume, commercial timber volume which would eventually lead to better estimations on differently managed teak plantation sites. By measuring the diameter at breast height alone, the developed log diameter-length tables could estimate the commercial log length according to specific diameter values which would finally lead to better commercial log estimation to compete with increasing demand along with different site conditions.

Keywords: height-diameter curve, relative taper curve, teak plantation

INTRODUCTION

The natural forest cover of Sri Lanka has declined drastically, and the remaining natural forest cover provides valuable environmental services. Forest plantations play a significant role as an alternative for natural forests to cater the timber demand. In dry and intermediate zones of Sri Lanka, *Tectona grandis* L.f (hereinafter teak) is the most commonly observed tree species in the household and government forest plantations (Ariyadasa, 2002). Individual total tree volume estimation of government teak plantations is currently based on existing volume tables developed by the Forest Department of Sri Lanka for each agro ecological zones. With changing market conditions, there is a need to precisely estimate tree volumes utilizing multiple upper stem merchantability boundaries. This is not currently possible with the existing total stem volume tables for teak plantations. The use of compatible volume taper equations approach can solve the upper stem values to any commercial limit (Jiang et al., 2005). However, taper systems do not currently in use for forests in Sri Lanka.

Majority of government plantations are not managed properly due to the reasons such as encroachment by people, elephant problems, fire hazards, etc. (Subasinghe, 2016). Comparative studies on differently managed teak plantations are less researched, especially in the Sri Lankan context. Subasinghe (2006) has developed a model to predict stem volume of plantation teak of Sri Lanka by considering the site variations. There is no conclusive study on how external site disturbances effect on government teak plantations of Sri Lanka. The timber need arises continuously for industrial purposes. Teak products demand shows an increasing trend, while age and extent (ha) of government teak plantations demonstrate an uneven-age-class pattern with various external disturbances (Ruwanpathirana, 2012). The missing thing is the commercial perspective of teak log volume

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for differently managed sites.

Numerous taper equations of various forms have been developed over the past (Kozak et al., 1969; Max and Burkhart, 1976; Kozak, 1988; Thomas and Parresol, 1991; Jiang et al., 2005; Brooks et al., 2008). In even-aged stands, site quality and stand density are the most affected parameters on the determination of allometric relationships (Whitford, 1991). Thus, the valuation of forest stand factors by allometric methods cannot be extrapolated further from the site and species for which they are defined and not even for the same site at different times. Therefore, it is important to evaluate the products supply from plantations by considering different site conditions. The results of such estimations will be used for the planning purposes and necessary calculations such as expenses, profits, etc. (Subasinghe, 2016).

Thus, the key aim of this study is to evaluate whether there is variability of the taper equations of teak depending on different site conditions, i.e., civil war and wild elephant threat on silvicultural practices and climatic condition under same maturity age of the teak plantations. Then we designed to obtain log diameter-length tables that explained how differently managed site conditions affect both growth and marketable log allocation.

MATERIALS AND METHODS

Study Area

Sri Lanka has conventionally been categorized into three agro ecological zones based on the annual rainfall, namely, dry, wet, and intermediate. Most of the teak plantations are established in dry (typically receives 800–1200 mm rainfall annually) and intermediate zones (average annual rainfall of 1,200–2,000 mm). Forest Department is the governmental body for the planting of forest plantations and State Timber Corporation maintains commercial activities of them. This study was based on three different matured teak plantation sites (stand age > 40 years) where distributed throughout the dry and intermediate zones to represent the main agro ecological zones which teak is grown as government forest total plantations. Figure 1 represents the agro ecological zones and external disturbances on teak plantations of Sri Lanka and study site locations. Table 1 represents the geographical and site information of those selected teak plantations. Standard management practices for teak plantations (Table 2) have been introduced by the Forest Department of Sri Lanka. The planting space is 3×3 m and 1,111 seedlings/ha are planted at the beginning (Maddugoda, 1993). For managed teak plantation of 40 years old, the Forest Department has determined the standards as 300 trees/ha at the final stage of felling. Four protection rounds are established for the purpose of weeding, boundary demarcation, and minimize the external illegal fellings. The goal of protection is having vigorous trees at the harvesting stage by minimizing external effects, even though those silvicultural practices have not been practiced properly in site I and II due to external disturbances.

The characteristics of the three sites were:

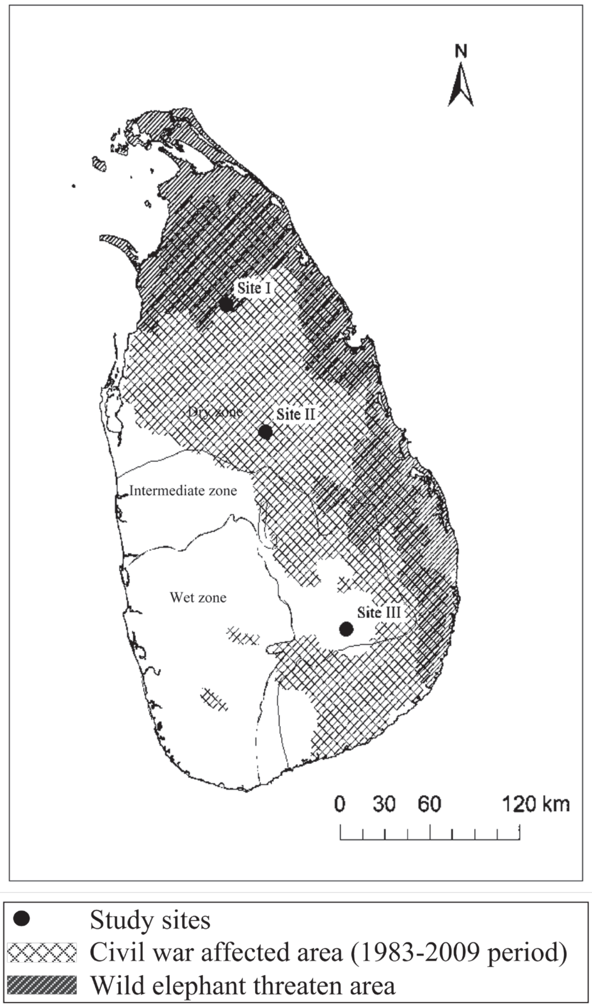

Fig. 1 External disturbances and study locations.

- Site I:
  - Punewa, a 44-year-old teak plantation which is in the Northern part of Sri Lanka, with an average annual temperature of approximately 27 °C.
  - Wild elephant habitats and civil war effect are the external disturbances. Civil war period of Sri Lanka was from 1983–2009 (Thiranagama, 2011) .
  - Poor silvicultural management due to inaccessibility to the field. So, the stands were not in their standards at the stage of final felling.
  - The density of bushes, wild trees, and large open areas were higher than the other two sites. Teak trees with a greater number of branches and dead trees were abundant.
- Site II:
  - Inamaluwa, a 51-year-old teak plantation which is located in the middle part of Sri Lanka, with an average annual temperature of approximately 26 °C.
  - The effect of wild elephants has been continued since the past (Fernando et al., 2011).
  - Less silvicultural practices due to the threat of wild ele-

Table 1 Geographical characteristics of the three teak plantation sites (State Timber Corporation, 2017)

Site	Location	Area (ha)	Age (yrs)	Altitude (m.a.s.l)	Slope (%)	Soil type
I	Punewa	20.00	44	101	5–10	RBE
II	Inamaluwa	29.20	51	167	5–10	RBE
III	Monaragala	13.50	48	179	5–10	RBE, IL

m.a.s.l, mean annual sea level (m); RBE, reddish brown earth soil; IL, immature loam soil (Panabokke, 1959).

Table 2 Standard silvicultural prctices for teak plantations of Sri Lanka (Ministry of Forestry and Environment, 1995)

Plantation age (years)	Management practices
6	Pre-commercial thinning
7–12	Protection
13	First thinning
14–19	Protection
20	Second thinning
21–29	Protection
30	Third thinning
31–39	Protection
40	Final felling

phants. So the maintenance of proper bole height is a hard task comparison to site III.

○ The relative abundance of wild plant species which are edible to wild animals.

● Site III:

○ Monaragala, 48-year-old plantation where located in the intermediate zone with an average annual temperature of approximately 27 °C.

○ Significant lush undergrowth with wild grasses and a smaller number of wild plants and shrubs.

○ No any identified external disturbances. Silvicultural practices were followed according to standards of the Forest Department (Table 2).

Data Collection and Analysis

Two steps were taken to ensure consistency between the product type dimensions that comprised the State Timber Corporation of Sri Lanka and the teak trees in forest plantations: (1) classification of teak products by considering economic value and diameter range (Teak product dimensions); and (2) field measurements in three teak plantations of Sri Lanka (teak plantation sites I to III). Teak logs, elephant poles, fence posts, and round poles are the main products of teak timber (State Timber Corporation, 2017). The teak log is the raw material for furniture production.

Data were collected at two times during 2016 and 2017. Square shaped sample plots were (20×20 m) established to take the standing tree measurements. 13 plots from site I, 5 plots from site II, and 8 plots from site III were set. Diameter at breast height (DBH) was measured at 1.3 m above ground and total tree height was measured of the standing trees by using the Tru-Pulse laser rangefinder. At the time of fieldwork, all the trees were felled, and those measurements were taken directly from the stand randomly. Sometimes there were practical limitations at the field to measure previously marked trees. Out of felled trees, diameter outside the bark (DOB) at breast height, bole height, and the heights at first branching point were measured. By considering the teak price manual of State Timber Corporation the minimum value for top end diameter of the felled tree was decided as 10 cm (detailed later). DOB was also measured at intervals of 2 m along the length of the stem until 10 cm over bark diameter reaches. Total of standing tree measurements of 177 trees and felled tree measurements of 175 trees was taken on two plantations from the dry zone (sites I and II) and one plantation from the intermediate zone (site III). After the two years of data collection, observations were recorded and used to develop height-diameter curves and allometric equations of the three different teak sites.

Height-DBH Curve

The relationship between tree height and DBH is considered to define height-DBH curve. The Henricksen equation was applied to simulate height-DBH curve (Eq. (1)):

$$H = a + b \log D \tag{1}$$

where H is the tree height, D is the DBH, and a and b are model parameters to be estimated. To our knowledge, there are no published studies on the standing tree height-DBH curves for each site of teak in plantation forests of Sri Lanka. Thus, we calculated the three curves based on the 164 standing tree samples for three study sites.

Taper Functions

Relative taper curve is the mathematical expression of the change in stem diameter as a function of stem height, which is calculated by tree conditions (Kozak and Smith, 1993). Measured field data (e.g. diameter at different heights) were converted into relative diameter and relative height to generate allometric relationships according to the following Eqs. (2) and (3):

$$Dr = D \times D_{0.9}{}^{-1} \tag{2}$$

where Dr is the relative diameter, D is the diameter at a specified height, and $D_{0.9}$ is the diameter at 1/10 tree height,

$$Hr = 1 - H \times Ht^{-1} \tag{3}$$

where Hr is the relative tree height, H is the tree height at a specified point, and Ht is the total tree height. Note that relative height

Hr ranges from 0 to 1 from the top end to bottom end of the tree.

Relative taper curve was created using Hr and Dr. Third order segmented polynomial taper function was applied according to results of Yin and Yamamoto (2013) to create the relative taper curves across an entire range of tree-height data. (Eq. (4)):

$$Dr = aHr^3 + bHr^2 + cHr \tag{4}$$

where a, b, and c are model coefficients to be estimated. The normal form factor, f (Osumi, 1959) of a tree in each site was calculated using estimated a, b, and c by following Eq. (5):

$$f = \int_0^1 Dr^2 \; dHr = \int_0^1 \left(aHr^3 + bHr^2 + cHr\right)^2 dHr \tag{5}$$

Timber Volume Calculation

Timber volume per tree was calculated based on the normal form factor, $D_{0.9}{}^2$ and Ht by the following Eq.(6):

$$\text{Timber volume per tree} = f \times (\pi / 4) \times D_{0.9}{}^2 \times Ht. \tag{6}$$

These kinds of volume equations derived from relative taper curve perform better compared to simple volume equations that only estimate total cubic volume or merchantable timber volume (Kozak, 2004) since volume taper equations can provide estimates of height at specific diameter, total and commercial stem volume from the ground.

Volume Estimation for Commercial Logs

In terms of productivity, the volume of material available in certain sizes and qualities must be estimated with high standards of precision and accuracy (Kozak et al., 1969). Hence the essential parameter is merchantable volume with respect to specific teak products. Teak timber grading ranges from 2–3 m log length as the State Timber Corporation grading standards. Teak logs are categorized and evaluated according to the diameter values of log and the log length depends on the defects and customer requirement at the field, except for super prime logs (3 m or over log length, ≥ 31.8 cm mid diameter, minimum surface and form defects). According to the price manuals of State Timber Corporation, the main commercial diameter values of teak logs of State Timber Corporation are 47.7 cm, 38.2 cm, 31.8 cm, 25.5 cm, 19.7 cm, 12.7 cm and 10.8 cm for teak poles. Those standard diameter values were converted into relative diameters and equivalent relative heights within the range of 0–1. The resulted relative heights were converted into actual log lengths using Eq (1). Average log lengths were obtained using sampled trees. From these items, merchantable volume per tree for each site with respect to log dimensions was determined. Stand merchantable volume per ha was derived by multiplying the merchantable volume per tree by the number of trees per ha. The relationship between the commercial product dimensions and monetary value of logs and poles are described in Fig. 2.

Log Diameter-length Tables

The materials used for the development of yield tables consisted of yearly inventories and results obtained in previous stages: height–DBH curves were used to estimate the standing tree height and taper curves for tree height at specific commercial dimensions of the logs. The tree height at specific diameter classes is obtained using the following Eq. (7):

$$\text{Tree height at } n^{\text{th}} \text{ diameter class} = \text{Relative height at } n^{\text{th}} \text{ diameter} \times \text{Total height of the tree} \tag{7}$$

Note that the tables concerned include the relationships between stand variables and the diameter specifications of teak logs as mentioned above.

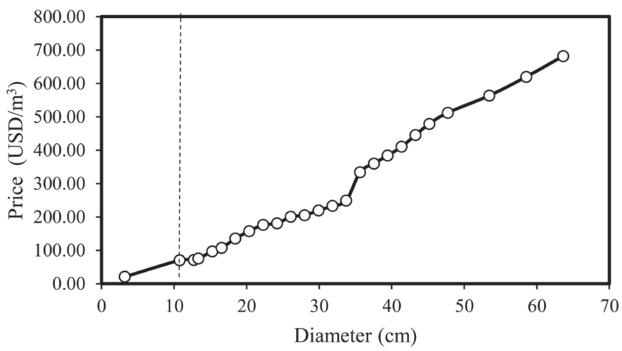

Fig. 2 Relationship between price of teak logs and top end diameter. Logs whose top end diameter is less than 10 cm are treated as poles.

RESULTS

Field Measurements

Outliers were removed from the field data to develop the height-DBH curve and relative taper curve. Table 3 shows a summary of the dendrometric characteristics of the selected trees as representatives of each site of the study. Among three sites, the highest average DBH of standing trees is 32.0 cm with the highest standard deviation in site I. Standing total height ranges from 16.2–20.4 m. The maximum average height and minimum average DBH of standing and felled trees have come from site III which is with the highest tree density.

Height-DBH Curve

The results of height-DBH curves of standing trees are shown in Fig. 3 and Table 4. Though fitness of the height-DBH curves are not necessarily good according to the R^2 values in Table 3, clear differences can be seen among the three curves in Fig. 3.

Relative Taper Curves and Normal Form Factor

The results of relative taper curves of felled tree measurements are shown in Fig. 4 and Table 5. The fitness of three curves are all good according to the R^2 values in Table 5, and slight differences can be seen among the three curves in Fig. 4. Among them, site III shows the best fitness. The difference in the parameter c of the equations are reflected in stem profiles of Fig. 4,

Table 3 Summary of dendrometric characteristics of selected felled and standing trees in the three sites

Site	Density (trees/ha)	Tree type	No of plots	*n*	DBH (cm)		Total height (m)	
					Average	*SD*	Average	*SD*
I	151	Standing	13	63	32.0	6.1	17.8	2.4
		Felled	−	90	30.6	4.7	17.5	1.1
II	199	Standing	5	51	31.8	5.7	16.2	2.5
		Felled	−	33	29.7	5.3	15.3	2.5
III	203	Standing	8	50	27.7	5.0	20.4	2.8
		Felled	−	35	27.0	4.4	19.7	2.4

n, number of trees sampled; *DBH*, diameter at breast height (cm); *SD*, standard deviation.

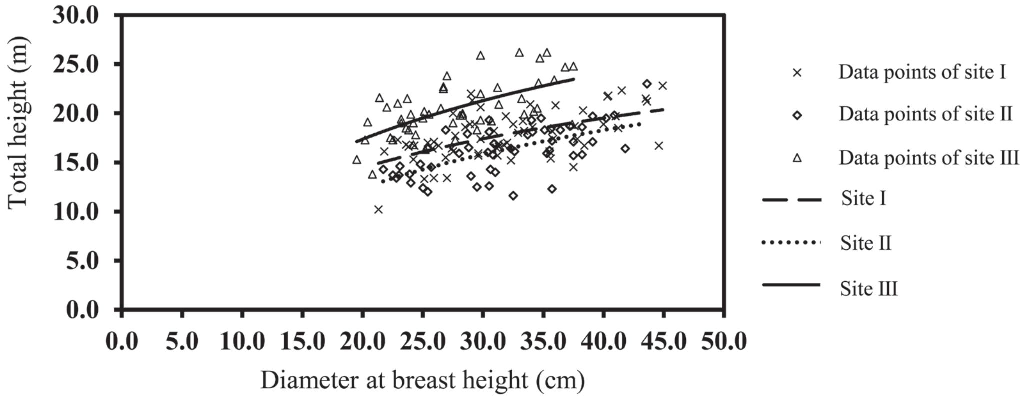

Fig. 3 Height-DBH curves of the sites.

Table 4 Height-DBH equations chosen for each three plantation sites

Site	*a*	*b*	R^2
I	−7.4777	7.3159	0.31687
II	−13.117	8.5110	0.39258
III	−11.640	9.6799	0.39674

R^2, coefficient of determination; *a* and *b*, coefficients of the model ($H = a + b\log D$).

Table 5 Relative taper (third order segmented polynomial) equations for three plantation sites

Site	*a*	*b*	*c*	R^2
I	2.6048	−4.2281	2.8158	0.85917
II	2.4643	−4.3249	3.0406	0.78866
III	3.4737	−5.7529	3.4887	0.87944

R^2, coefficient of determination; *a*, *b*, and *c*, coefficients of the model ($Dr = aHr^3 + bHr^2 + cHr$).

which site III has the least tapering stem followed by sites II and I. In addition, the normal form factors for the sites I, II and III are 0.391, 0.440 and 0.433 respectively (Table 6), which lead to calculate the timber volume of a teak tree by Eq. (6). This normal form factor was also the highest in the site III.

Total Cubic Volume and Merchantable Volume

Stand characteristics including timber volumes per tree and per hectare are presented in Table 6. The average total tree height and bole tree height are the highest in the site III, which is a good indicator of proper management practices within the site. The highest average total cubic volume is in the site I, which is 0.500 m^3, while stand cubic volume per hectare is maximum in site II which is 96.6 m^3. Parameter *c* of relative taper equation of site III provides ideal perfection for the equations to lead the highest merchantable volume per tree which is 0.301 m^3 among three sites.

Table 7 represents the average merchantable log volume and its percentage toward total cubic volume as well. Further, it is essential to classify elephant poles, fence poles, and round poles production. Finally, the remaining volume can be considered for firewood.

Comparison of stand characteristics with Forest Department standards is presented in Table 7. All three sites exceed the 50% cut off the margin of commercial log volume standard of the Forest Department, while the maximum percentage of logs comes from the site III which is 67%. It is evident that site III represents a close relation with standards of the Forest Department for merchantable volume.

Log Diameter-length Tables

Yield tables of each site are presented in Tables 8, 9, and 10 for the DBH range of 18–55 cm. These are the predictions of log lengths of the standing trees for the commercial diameter

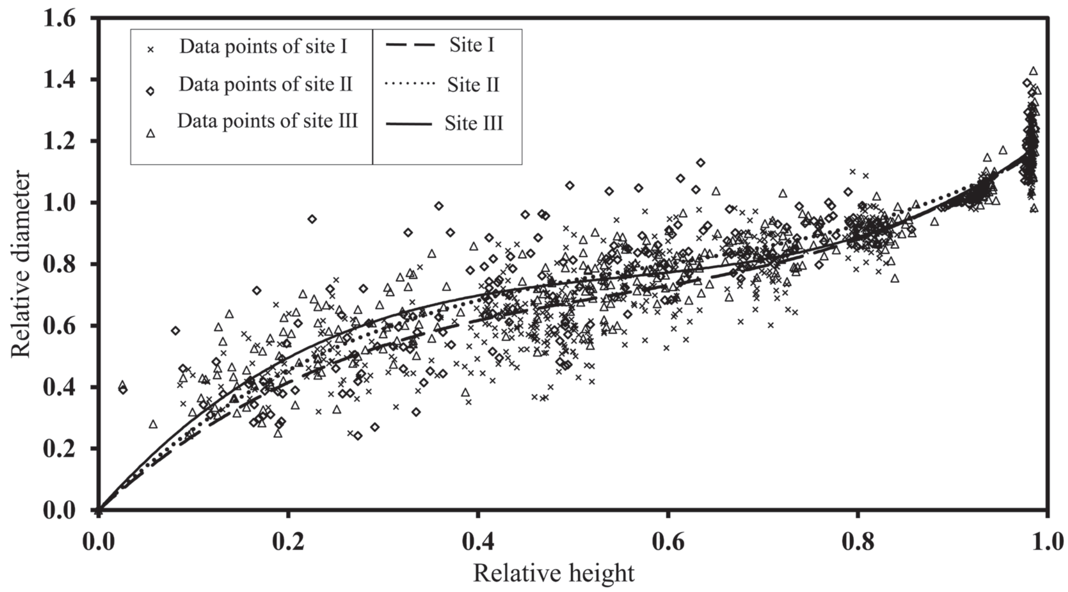

Fig. 4 Relative taper curves of the sites.

Table 6 Calculated stand characteristics of each site

Properties	Site		
	I	II	III
Density (trees / ha)	152	199	205
Total no. of trees	3,037	5,830	2,752
Average DBH (cm)	32.0	31.8	27.7
Average total height (m)	17.5	15.3	19.7
Average bole (m)	6.3	6.1	11.2
Normal form factor	0.391	0.440	0.433
Average basal area at 1/10 height (m^2)	0.0729	0.0721	0.0526
Average total cubic volume (m^3)	0.500	0.486	0.449
Stand cubic (m^3/ha)	75.9	96.6	91.9
Average merchantable volume (m^3)	0.253	0.253	0.301
Stand merchantable volume (m^3/ha)	38.5	50.3	61.6

Table 7 Comparison of stand characteristics in each site with standards of Forest Department

Properties	Site			Standard of Forest Department
	I	II	III	
Age (years)	44	51	48	40
No of trees / ha	152	199	204	300
Total cubic volume/tree (m^3)	0.500	0.486	0.449	0.714
Average merchantable volume/tree (m^3)	0.253	0.253	0.301	0.357
Percentage of merchantable volume	51%	52%	67%	50%

dimensions of logs. According to these tables, site III had the highest bole height range, followed by sites II and I. With these log diameter-length tables it is possible to know the number of logs and number of poles which comes from an individual tree.

DISCUSSION

Taper Curve

Consisting with Fig. 4, site III had the largest value of parameter *c*, followed by sites II and I. The taper curve equations obtained in this study clearly show that site III is an excellent region for teak growing which has the least tapered stem in comparison to the other sites. It describes the proper silvicultural

Table 8 Upper tree height prediction for a range of DBH – site I (Punewa)

DBH	Total height	Bole height	Height (m) at diameter (cm)						
(cm)	(m)	(m)	47.7	38.2	31.8	25.5	19.7	12.7	10.8
18	13.67	5.77					0.69	4.48	6.32
19	14.06	5.82					1.07	5.26	7.05
20	14.44	5.86					1.36	6.07	7.80
21	14.80	5.91					1.79	6.78	8.32
22	15.14	5.95					2.11	7.39	8.97
23	15.46	5.99				0.54	2.31	8.14	9.50
24	15.77	6.03				0.84	2.79	9.06	10.03
25	16.07	6.07				1.30	3.71	9.57	10.57
26	16.36	6.10				1.75	4.24	9.94	10.96
27	16.63	6.14				2.24	4.78	10.60	11.35
28	16.90	6.17			0.30	2.59	5.64	10.98	11.74
29	17.16	6.20			0.47	2.95	6.53	11.35	12.12
30	17.41	6.23			0.79	3.17	7.12	11.71	12.51
31	17.65	6.26			0.97	3.38	7.57	12.08	12.89
32	17.88	6.29			1.31	3.93	8.03	12.45	13.27
33	18.10	6.32			1.66	4.33	8.49	12.81	13.48
34	18.32	6.35		0.17	2.03	4.73	8.95	13.35	13.85
35	18.53	6.37		0.51	2.40	5.14	9.43	13.71	14.06
36	18.74	6.40		0.70	2.78	5.39	9.91	13.91	14.43
37	18.94	6.42		0.88	3.17	5.99	10.75	14.27	14.62
38	19.13	6.45		1.25	3.39	6.42	11.24	14.45	14.99
39	19.32	6.47		1.45	3.61	7.23	11.74	14.81	15.17
40	19.51	6.49		1.83	4.02	7.49	12.06	14.99	15.54
41	19.69	6.52		2.03	4.44	8.14	12.39	15.35	15.72
42	19.87	6.54		2.43	4.86	8.97	12.71	15.52	16.08
43	20.04	6.56	0.19	2.65	5.29	9.45	13.04	15.68	16.25
44	20.21	6.58	0.38	3.05	5.73	9.74	13.36	16.04	16.61
45	20.37	6.60	0.58	3.47	6.17	10.22	13.69	16.20	16.78
46	20.53	6.62	0.97	3.70	6.62	10.71	14.02	16.35	17.13
47	20.69	6.64	1.18	4.13	7.07	11.20	14.35	16.70	17.29
48	20.84	6.66	1.39	4.36	7.93	11.50	14.68	16.86	17.45
49	20.99	6.68	1.60	4.80	8.20	12.00	14.80	17.21	17.81
50	21.14	6.70	2.02	5.04	8.48	12.31	15.13	17.35	17.96
51	21.29	6.72	2.03	5.49	8.75	12.62	15.46	17.50	18.11
52	21.43	6.73	2.46	5.95	9.44	13.13	15.59	17.85	18.26
53	21.57	6.75	2.69	6.41	9.92	13.44	15.92	17.99	18.61
54	21.71	6.77	2.92	6.67	10.42	13.96	16.04	18.33	18.75
55	21.84	6.78	3.15	6.93	10.70	14.27	16.37	18.47	18.89

practices done during the growing period.

As far as the general volume equations of Forest Department of Sri Lanka is concerned, the site differences may not affect the final merchantable volume. It is essential to use the developed taper curves to find the merchantable volume since it includes the effect of site differences. Nevertheless, these curves should be confirmed in the future with a sample covering whole ranged variation of the teak plantations of their age of 40s.

Timber Volume

The taper and the volume equations are each dimensionally compatible and analytically consistent with each other, since volume, is the combined taper function (Sharma and Oderwald, 2001). Parameter *c* of taper curve directly relates with timber volume of each site. The lowest density can be seen at the site I which is 151 trees per ha. The stand merchantable volume of the site I also lower compared to the other two sites. The causes behind these scenarios are poor management due to civil war and wild elephant threat. Those causes have lead heavy undergrowth, large open spaces with the plantation and larger number of branches of teak trees with irregular thinnings. Due to the same reasons, the average bole heights of sites I and II were

Table 9 Upper tree height prediction for a range of DBH – site II (Inamaluwa)

DBH	Total height	Bole height	Height (m) at diameter (cm)						
(cm)	(m)	(m)	47.7	38.2	31.8	25.5	19.7	12.7	10.8
18	11.48	6.14					0.34	4.71	6.32
19	11.94	6.13					0.72	5.37	6.93
20	12.38	6.12					1.24	6.07	7.68
21	12.80	6.12					1.79	6.78	8.19
22	13.19	6.11					2.37	7.39	8.71
23	13.57	6.10				0.14	2.71	8.01	9.23
24	13.93	6.10				0.56	3.20	8.92	9.75
25	14.28	6.09				1.00	3.71	9.42	10.42
26	14.61	6.08				1.46	4.09	9.94	10.81
27	14.93	6.08				1.79	5.38	10.45	11.20
28	15.24	6.07				2.29	5.95	10.98	11.59
29	15.54	6.07			0.16	2.80	6.53	11.35	11.97
30	15.83	6.06			0.47	3.32	6.97	11.71	12.35
31	16.11	6.06			0.97	3.87	7.73	12.08	12.73
32	16.38	6.05			1.31	4.26	8.19	12.29	13.10
33	16.64	6.05			1.66	4.83	8.65	12.65	13.31
34	16.90	6.04			2.03	5.41	9.12	12.84	13.69
35	17.14	6.04			2.57	5.83	9.94	13.20	14.06
36	17.38	6.03		0.35	2.96	6.43	10.26	13.56	14.25
37	17.62	6.03		0.70	3.35	7.05	10.57	13.92	14.62
38	17.84	6.03		1.07	3.75	7.49	10.88	14.27	14.81
39	18.06	6.02		1.45	4.34	7.95	11.20	14.45	15.17
40	18.28	6.02		1.83	4.75	8.59	11.52	14.81	15.35
41	18.49	6.01		2.22	5.18	9.06	12.02	14.98	15.72
42	18.69	6.01		2.62	5.80	9.53	12.53	15.33	15.89
43	18.89	6.01		3.02	6.24	9.83	12.85	15.49	16.25
44	19.09	6.00		3.44	6.49	10.31	13.17	15.85	16.42
45	19.28	6.00	0.58	3.86	7.13	10.80	13.50	16.00	16.58
46	19.47	6.00	0.39	4.28	7.59	11.10	13.82	16.35	16.94
47	19.65	5.99	1.18	4.52	8.06	11.59	14.15	16.51	17.10
48	19.83	5.99	1.39	4.96	8.53	11.90	14.48	16.86	17.25
49	20.01	5.99	1.60	5.40	8.80	12.20	14.80	17.01	17.61
50	20.18	5.98	2.02	5.85	9.28	12.71	14.93	17.35	17.76
51	20.35	5.98	2.24	6.31	9.77	13.02	15.26	17.50	17.91
52	20.51	5.98	2.67	6.77	10.26	13.33	15.59	17.64	18.26
53	20.67	5.97	2.89	7.03	10.54	13.65	15.71	17.78	18.40
54	20.83	5.97	3.13	7.71	10.83	13.96	15.42	18.13	18.54
55	20.99	5.97	3.57	7.98	11.33	14.27	16.16	18.26	18.68

lower than site III. Natural forests are surrounded by those teak plantations, so habitats of wild elephants has been overlapped with teak plantations. It is hard to find a good solution to minimize the elephant disturbances on plantation management. The civil war (1982–2009) has been finished, forestry workers could not continue silvicultural practices at site I properly during that period.

The average total tree height (19.7 m/tree) and average merchantable volume (0.301 m^3/tree) of the site III show the highest when compared to the other sites. Commercial productivity which is 67% out of total cubic volume also comes from the site III. Thus, it is evident that the site III has the most desirable commercial parameters on the other two sites. It has the highest values for average tree height, normal form factor, and tree density. The main factors controlling the distribution and growth of teak are rainfall, soil moisture, temperature, light, geology, soil pH, and calcium and other mineral elements in soil (Kaosa-ard, 1989). Actually, it grows best and reaches large dimensions in a warm-moist tropical climate with rainfall ranging from 1250–2500 mm per year associated with a marked dry period of 3–5 months, (Kaosa-ard, 1977) which is mostly matched with the site III. The optimum temperatures for better growth and de-

Table 10 Upper tree height prediction for a range of DBH – site III (Monaragala)

DBH (cm)	Total height (m)	Bole height (m)	Height (m) at diameter (cm)						
			47.7	38.2	31.8	25.5	19.7	12.7	10.8
18	16.34	11.41					0.33	7.19	10.46
19	16.86	11.38					0.98	8.60	11.47
20	17.36	11.35					1.52	9.89	12.15
21	17.83	11.32					2.08	11.06	13.02
22	18.28	11.30					2.67	11.88	13.53
23	18.71	11.27					3.29	12.72	14.22
24	19.12	11.24				0.38	4.12	14.15	14.92
25	19.52	11.22				1.17	4.97	14.25	15.42
26	19.90	11.20				1.59	5.86	14.92	15.92
27	20.26	11.17				2.03	6.96	15.40	16.41
28	20.62	11.15				2.68	8.11	15.87	16.90
29	20.96	11.13				4.19	9.28	16.34	17.39
30	21.28	11.11			0.64	4.68	10.48	16.81	17.88
31	21.60	11.09			1.30	5.62	11.71	17.28	18.14
32	21.91	11.07			1.31	6.13	12.53	17.75	18.62
33	22.21	11.06			1.78	6.66	13.36	18.21	18.87
34	22.49	11.04			2.02	7.87	14.21	18.67	19.35
35	22.78	11.02			2.28	8.43	14.85	18.90	19.59
36	23.05	11.00		0.46	3.23	8.99	15.49	19.36	20.05
37	23.31	10.99		0.93	3.73	9.56	15.90	19.82	20.28
38	23.57	10.97		1.18	4.71	11.08	16.55	20.04	20.51
39	23.82	10.96		1.67	5.24	11.91	16.97	20.25	20.73
40	24.07	10.94		1.93	5.78	12.76	17.39	20.70	21.18
41	24.31	10.93		2.43	6.32	13.37	17.81	20.90	21.39
42	24.54	10.91		2.94	6.87	13.99	18.23	21.10	21.60
43	24.77	10.90		3.22	7.93	14.86	18.65	21.55	22.04
44	24.99	10.89		3.75	9.00	15.49	19.07	21.74	22.49
45	25.21	10.87	0.50	4.29	10.08	16.13	19.24	21.93	22.69
46	25.42	10.86	0.76	4.83	10.68	16.78	19.66	22.37	22.88
47	25.63	10.85	1.03	5.38	11.28	17.17	20.08	22.55	23.07
48	25.83	10.83	1.29	5.94	11.88	17.31	20.50	22.73	23.25
49	26.03	10.82	1.56	6.25	12.50	17.70	20.41	22.91	23.43
50	26.23	10.81	1.84	6.82	13.64	18.10	20.57	23.34	23.61
51	26.42	10.80	2.11	7.40	14.00	18.76	21.77	23.51	24.04
52	26.61	10.79	2.39	8.25	14.90	19.42	20.87	23.95	24.21
53	26.79	10.78	2.68	8.84	15.54	19.56	22.08	24.11	24.38
54	26.97	10.77	3.24	9.71	16.18	19.96	22.24	24.28	24.82
55	27.15	10.75	3.80	10.32	16.83	20.36	22.39	24.44	24.98

velopment of teak are between 27–36 °C during the daytime and between 20–30 °C during the night time (Gyi, 1972; Kaosa-ard, 1977). Temperature ranges have no vast variances among three sites. The range of light intensity of 75–95% (Bhatnagar,1966), and the pH range is between 6–7.5 (Kulkarni,1951) which are not being drastic differences among those sites. It is evident that the higher productivity of site III has been caused by mainly rainfall, optimum dry period, and proper management practices with minimum external disturbances.

The conventional volume equations of the Forest Department for teak is developed mainly by considering agro ecological zones of Sri Lanka. The site quality parameters have not been considered yet to prepare yield tables. The three sites given here could be placed around the best quality (site III) and the poorest quality is from the site I for the commercial products. Civil war and elephant threat of site I and site II have been affected badly for the silvicultural practices since the planting of teak in government plantations. The result of 61.6 m^3/ha of stand merchantable volume at the age of 48 years in site III is considered as average quality site in Sri Lanka according to the comparison with the Forest Department standards, though some teak planting schemes planned for this region claimed to reach higher volume which is 107 m^3/ha (Ministry of Forestry and Environment, 1995) which was heavily against figures obtained in this study. Table 7 can be used as a base to interpret cubic volume results of government teak plantations all over Sri Lanka.

Log Diameter-length Tables

The conventional yield table has been developed for the whole island only using climatic conditions by the Forest Department of Sri Lanka. The new table consists of the commercial break-up diameters, instead of normal diameter categories defined by the conventional one. The new criterion for our table use is, moreover, based on a site condition study, which the conventional yield tables lacked. Our new tables are fully detailed in their effect of differently managed site conditions, thus providing a more useful management tool from the long-term point of view. Table 10 can be used for the plantations with standard management practices. Tables 8 and 9 represent different distubances with less silvicultural management. Note that currently there is no practice of standard length for sawlog in the timber trade and the length is depending on the commercial use of the log except for super prime log grade. Considering that study areas cover a wide spectrum of sites, we affirm that the proposed tables, though developed from three sites, can be used in all those differently managed teak plantations of Sri Lanka.

CONCLUSION

The results suggest that, at least under homogeneous stand age, the allometric relationships may change depending on site conditions of government teak plantations. The yield tables developed in this study could be provisionally adopted for teak plantations managed under different conditions in Sri Lanka. Those seem to be the best tools for designing economical profitability and are also helpful in matters concerning forest inventory and management. They are also a necessary tool in resource planning essential to forest policy design.

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