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Original Article

Buttressing impact on diameter estimation in plantation teak (*Tectona grandis* L.f.) sample trees in northern Thailand

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ABSTRACT

Buttressing consists of ground-upward deformations from the circular cross section of a tree and can be quite pronounced in tropical species, thus making the measurement of lower diameters in older trees especially problematical in collecting accurate sample tree data. A technique to correct for buttress distortion of diameter estimates from girth tape measurement was applied using photographic images of cross sections at known lower bole heights on 331 plantation teak sample trees in eight plantations over four provinces in northern Thailand. Image scaling and image correction for distortion were used to obtain an equivalent diameter based on the actual digitized sectional area and standard geometry. The estimates of diameters over buttressing exceeded equivalent sectional area diameter estimates by more than a nominated 3% difference for at least one measuring height in the lower bole on 73% of the trees measured. The results of the *t*-test analysis indicated that the two sets of diameters were highly significantly ($p < 0.001$) different with the data measured using the girth tape overestimating the actual buttressed sectional area based on the sectional analysis. The study indicated that pronounced buttressing is common, especially in the lower bole of plantation teak trees and correction is essential where such sample tree measurements are to be used in taper modeling to avoid introducing a potentially large overestimation bias into the model.

Introduction

The terms ‘buttressing’ and ‘fluting’ have been used to define deformations from the ground upward of the circular cross section of a tree (Mollick et al., 2005) which have also been described as “lateral flanges joining the roots and the trunk” (Clair et al., 2003). They are often attributed to buttress roots (Schmidt, 1997) and typically develop with age (Kjaer et al., 1995) and tree size (Crook et al., 1997; Zhiyuan et al., 2013) and persist once formed (Chapman et al., 1998).

Newbery et al. (2009) citing Richards (1996) defined buttresses as “external woody lateral-vertical structures” resulting from early surface root growth and as being distinctive, but rarely found outside tropical rainforest, though Walsh and Dawson (2012) investigated their occurrence in the bald cypress wetlands of Southeastern USA. Furthermore, Parresol and Hotvedt (1990) referred to the “fluted basal swell” in bald cypress that made measurement at breast height (1.3 m above ground on the uphill side of the tree) often pointless since the buttress dimensions mostly bore no meaningful relationship with the wood volume in the lower bole. The purpose of buttressing is still being debated with many arguing it is a structural response by the tree to forces such as major wind or an asymmetrical canopy (Young and Perkocha, 1994; Nicol and Ray, 1996; Schmidt, 1997; Mehedi et al., 2012)—albeit with some contradictory reports such as Lewis (1988) and Clair et al. (2003)—or that it develops in younger trees as a consequence of surface roots spreading out to access limited nutrient resources (Pandey et al., 2011) or that it has some implied relationship with slope (Chittibabu and Parthasarathy, 2000) or more recently that it is a response to flooding (Walsh and Dawson, 2014) or regulates soil moisture and promotes seedling diversity (Tang et al., 2014).

Fallah et al. (2012) discussed an out-of-roundness index based on the maximum and minimum diameter at a given height and found that for three hardwood species in Iran, this index was significantly different for stump height compared to diameter at breast height. However, while useful for relative comparisons at different heights or among species, such an index does not help to quantify diameters in the buttressed part of the stem for actual sectional area or volume calculations or to develop a taper model,

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which is essential for log product optimization scenario analysis (Warner, 2007, 2016).

Taper is the general decrease in the regular outline of a solid body from its base to its tip (Schreuder et al., 1993). Tree taper equations (derived from representative diameter measurements overbark and underbark at various known heights up sample trees) are important because they underpin reliable estimates of different wood products and their value (Goodwin, 2009), which are essential to quantify expected commercial harvest returns (Salam and Pelkonen, 2012). Taper equations have also been applied to help in determining biomass and carbon sequestration to quantify Greenhouse gas emissions (for example, Fonweban et al., 2011).

Walsh and Dawson (2014) achieved limited success (57% of the variation was explained by their model though some input variables were not easily measured) in the estimation of the percentage of the total stem volume in buttresses using the frustra of buttresses and the stem above the buttress. Mollick et al. (2005) used four classes to define the severity of buttressing at 1.0 m from the ground in teak in Bangladesh, while Kjaer et al. (1995) used an index based on the buttress length, number and severity. However, neither of these approaches could be used to estimate the actual sectional area within any part of the buttressed section of the lower bole. Some related work using photogrammetry has been reported and shows promise (for example, Dean, 2003 and Nölke et al., 2015), but to date has not been widely applied in practice.

Teak has long been recognized as a highly valued timber species (Thorel, 1873; Forest Industry Organization, 2015) with an increasing reliance on plantation grown stands for a sustainable sawlog supply; for example in Thailand, only plantation teak is now allowed to be commercially harvested (see Warner, 2016 for more detail).

Consequently, the aim of the current study was to quantify whether buttressing was an issue requiring correction in lower bole diameter measurements used to compile a database for taper model development based on representative diameter and height measurements obtained from destructive sampling of plantation teak trees in northern Thailand.

Materials and methods

The sampling procedure applied to each sample tree has been described in Warner et al. (2016) and involved eight commercial teak plantations aged 10–45 yr in four northern Thai provinces. Briefly, accurate modeling of taper to determine different high-value products was required in the lower bole, so in each felled sample tree, girth measurements were taken above ground level at around 0.3 m, 0.5 m and 0.8 m and at breast height. Digital photographs of chainsawn cross sections including a metric scale measure were taken at these lower sampling heights where there appeared to be buttressing, so that image analysis could be carried out post sampling if required (an example is shown in Fig. 1 and discussed in more detail below).

Conventional girth tape measurements can produce misleading results where there is pronounced buttressing, as at such points on the bole, the tape clearly does not follow the actual outside perimeter of the tree and includes "empty" areas where there is no wood, depending on the size and amount of buttressing. This issue was noted in the study of teak taper in Tanzania by van Zyl (2005) but could not be addressed in that study as diameter measurements were taken using an optical dendrometer.

However, in the current study, girth measurements and photographs of the cross sections provided more information and Fig. 1 shows an example for sample tree 308 at a height of 0.5 m which illustrates this problem. The girth tape estimate (the outer dashed line) defines the maximum shape formed by a straight line joining the outermost extreme convex points on the stem cross section. As can be clearly seen in Fig. 1, the over-buttress girth estimate can be a substantial overestimate of the actual sectional area of wood in the bole at this height, which would introduce overestimation errors in taper modeling and any subsequent sectional area and volume estimation using such a girth estimate.

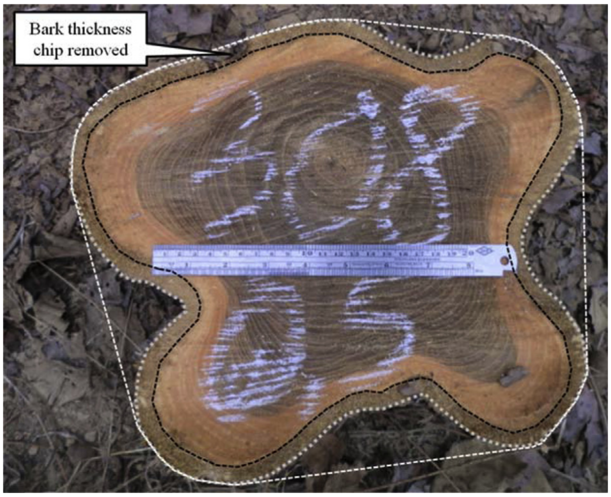


Fig. 1. Digitized outlines for sample tree 308 at 0.5 m height using the Farm Forestry Toolbox (Warner, 2007), where outer light dashed line = girth tape estimate of the girth; central dotted line = girth overbark based on actual perimeter; inner dark dashed line = underbark girth which is the perimeter of the actual underbark sectional area; and the bark visible where the bark chip was removed to the cambium in fact represents the back edge of the hole where the chip was removed.

To address this concern, an approach was adopted to account for distortion in the photographic images of any cross sections taken where buttressing was pronounced and to estimate the actual amount of wood where pronounced buttressing made using the overbark girth measurement to derive an inferred tape sectional area an unacceptable (nominally more than 3% different as detailed later) overestimate of the digitized sectional area. Consistent with the approach of Dean (2003), the freshly crosscut sections were photographed in the middle of the field of view and stored as digital images using sufficient resolution to discern the cambium, with a wide range of image file sizes (typically 250–6000 kilobytes) satisfying this constraint. A scaled ruler or length tape in each image (which would be subjected to the same amount of distortion from the camera lens as the sectional image on which it was placed) was used for calibration as described below.

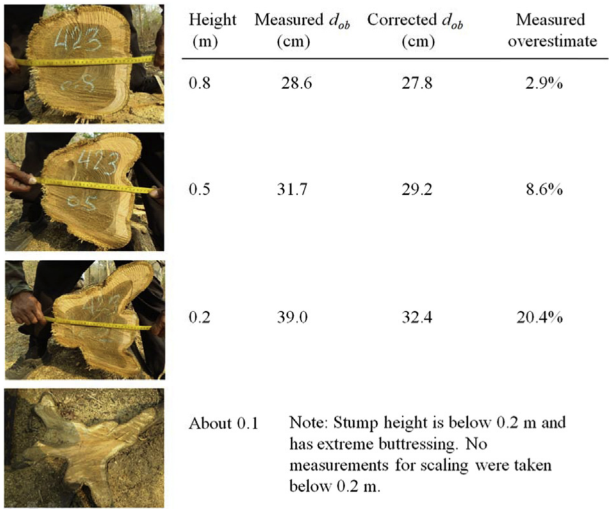
With reference to the length tape or steel ruler gradations included in the image, each digital image of a cross section at a measurement point with suspected pronounced buttressing was scaled using the Survey tool (version 5.3; Private Forests Tasmania; TAS, Australia) of the Farm Forestry Toolbox (Warner, 2007), freely available from www.pft.tas.gov.au. Then, the girth overbark for the same cross section was digitized, applying the same process that governed where the actual girth tape would have been physically placed around the extreme points on the perimeter (Fig. 1). The interface between the bark and the cambium was clearly visible in all images and so the underbark sectional area could be digitized and this was used to determine the equivalent underbark diameter (*EQDUB*) using Eq. (1):

$$EQDUB = \sqrt{(K/\pi * SAUB)} \tag{1}$$

where *EQDUB* is the equivalent underbark diameter for a circular cross section (measured in centimeters), *SAUB* is the sectional area underbark (measured in square meters) digitized from the scaled image, π is the mathematical constant (≈ 3.14159) used in circular geometry and K is a constant value (4×10^4) that includes a correction to present the diameter in centimeters based on the sectional area in square meters. In many images, one or more of the three sampling points where a bark chip was removed to measure bark thickness were visible and provided an additional check on the position of the cambium in the image (for example, see Fig. 1).

Finally, the *EQDUB* value was corrected using the ratio of the measured girth overbark to the equivalent digitized girth overbark which provided adjustment for any scaling or distortion errors from using the photograph, as the estimate of the girth measurement from the image involved joining the points on the perimeter of the cross section in the same way that the girth tape would. Thus, the distortion and scaling errors associated with the camera and the scaling process could be expected to be similar for the underbark sectional area and the ratio of the actual overbark girth measurement (using the girth tape) to the estimated overbark girth from the image (shown by the outer dashed line in Fig. 1), as these two lines occupied similar parts of the image and thus this approach provided a general correction factor. A similar procedure was used to determine the equivalent overbark diameter and the difference between these two corrected amounts was the respective double bark thickness.

A nominated absolute minimum of 3% difference between the diameter overbark based on the measured girth and the diameter overbark equivalent to the actual sectional area from the cross section image at the height of measurement (denoted as the critical difference factor or CDF for sectional area) was adopted to justify correcting the diameter overbark estimate obtained using the fiberglass tape as shown by the example in Fig. 2. This nominal level was considered to be consistent with the girth tape being generally in contact with the bark at the measurement height with only one or two small areas where there was some out-of-roundness; also for the size range of the sample trees, this represented a mean difference of about 1 cm, which was considered a sufficient amount to be of concern and not readily attributable to slight differences in measuring technique by a competent measurer. Furthermore, the use of a standard difference (3%) could be applied in a systematic manner to avoid any bias in accounting for the overestimation of the sectional area where buttressing was pronounced.



Height (m)	Measured d_{ob} (cm)	Corrected d_{ob} (cm)	Measured overestimate
0.8	28.6	27.8	2.9%
0.5	31.7	29.2	8.6%
0.2	39.0	32.4	20.4%
About 0.1	Note: Stump height is below 0.2 m and has extreme buttressing. No measurements for scaling were taken below 0.2 m.		

Fig. 2. Example of typical rapid change in degree of buttressing of diameter overbark (d_{ob}) in lower bole of sample tree 423 aged 35.7 yr; (note: correction was applied using the Farm Forestry Toolbox technique described in the text above).

The "t.test" function in the R package (R Core Team, 2015) was used to calculate a paired *t*-test for the diameters at measured heights where there was greater than a 3% difference between the girth tape measurement and the *EQDUB* value.

Results

In total, 331 trees were measured and the diameter at breast height overbark was in the range 15.8–53.2 cm and the total height range was 12.4–32.9 m. More detailed summary statistics are provided in Warner et al. (2016).

As a cross section was not photographed for all lower bole height measurements (that is, where the measuring team did not consider it necessary or in a few cases where the photograph was not suitable for accurate sectional analysis), a few records were excluded from the final database to avoid the inclusion of non measured pronounced buttressing where the change in diameter from a comparison with adjacent lower bole measurements suggested the buttressing effect on the diameter exceeded 3%.

For example, Table 1 shows the values for determining these calculations for sample tree 308 at a height of 0.5 cm and indicates that using the forest measurements of girth and bark thickness would result in a calculation that overestimated the underbark diameter by 14.1% based on the equivalent diameter method described above (see Table 1 and also Fig. 1 for the photograph of the buttressing at 0.5 m on the stem of tree 308). As the aim of the measurement was to determine the diameter underbark in the tree, which in turn was used to estimate the sectional area and thence the stem product volume, it is clear that without the adjustment described above, the diameter underbark and volume estimates for similar buttressed sections of teak trees would be substantially overestimated or if a diameter above the buttressed part of the tree were used as a substitute, then underestimation could result (reported to be up to 18.5% for aboveground dry biomass by Ngomanda et al., 2012).

Of the 331 sample trees measured at 499 sample points for pronounced buttressing in the lower bole, the CDF was exceeded at one or more measured heights in 241 (73%) trees ranging from 40% to 89% of the trees for each of the eight plantations sampled (Table 2). Such high levels of buttressing in all plantations indicated that it is a common characteristic that needed to be taken into account in the development of a taper model.

Fig. 2 shows the typical decline in buttressing with increased height in one of the older teak trees sampled in the study.

Overall, 60% (238 out of 399) of the overbark diameter values that had been derived from the images that exceeded the CDF were at 0.2 or 0.3 m up the bole, reducing to 29% and 11% at heights of 0.5–0.6 m and 0.7–0.8 m, respectively (Table 3).

There were 399 cross sections where the overbark diameter calculated from the image differed by more than the nominal CDF of 3% (referred to below as the adjusted data) from the overbark diameter determined using the initial girth tape measurements (Table 3). The two sets of diameters for these points were analyzed to see if they were statistically different using a paired *t*-test. A one-tailed *t*-test was appropriate in this case, as the test was to determine if the mean difference was significantly greater than zero (that is, the girth tape measurement over buttressing was significantly more than the digitized estimate based on the actual sectional area).

The results of the *t*-test analysis of the 399 paired records ($t = 30.5524$, degrees of freedom $= 398$, p-value $< 2.2 \times 10^{-16}$) indicated the p-value was very low and so the null hypothesis of no difference between the diameter overbark derived from the two different procedures was rejected. There was very strong evidence ($p < 0.001$) that the two sets of diameters were highly significantly different with the data measured using the girth tape

Table 1
Parameters from sample tree measurements and scaled photograph to estimate underbark sectional area of pronounced buttressing at 0.5 m on stem of sample tree 308.

Parameter	Value
A. Girth overbark measured in forest using fiberglass girth tape	106.7 cm
B. Conversion of A to diameter overbark ($d_{ob} = \mathrm{A}/\pi$)	34.0 cm
C. Twice bark thickness (mean from 3 measurements)	2.1 cm
D. Diameter underbark (d_{ub}) using forest measurements only (B–C)	31.9 cm
E. Sectional area underbark (SAUB) based on forest calculations ($\pi D^2/40{,}000$)	0.07974 m^2
Measurements from scaled photograph	
F. Girth overbark of actual perimeter from image	115.4 cm
G. Estimate of tape measurement of girth overbark from image	105.6 cm
H. Correction factor to adjust for image distortion applied to image to get actual girth overbark (A/G)	1.0104
I. Digitized SAUB from scaled photograph	0.06002 m^2
J. *EQDUB*[a] (SQRT[b](I × 4/π))	27.6 cm
K. Final $d_{ub} = EQDUB$ adjusted for image distortion using the ratio of girth overbark measurements in the forest and from the image (J × H)	27.9 cm
L. Overestimate of d_{ub} based on forest measurements compared to d_{ub} based on corrected sectional area (D/K)	14.1%

[a] Equivalent diameter underbark (d_{ub}) derived from the image sectional area underbark (SAUB) assuming a circle.
[b] Square root.

Table 2
Numbers of sample trees by plantation with diameter overbark differences due to identified buttressing at lower bole heights (trees could have multiple buttress-measured heights.).

Plantation[a]	Number of sample trees	Buttressing measured Difference[b] in d_{ob}		Percentage of trees
		≤3%	>3%	>3%
KMK	54	7	48	89%
WGC	51	36	40	78%
MMS	35	8	28	80%
MMJ	52	9	41	79%
MMM	42	1	32	76%
TGK	33	5	21	64%
MHP	19	2	13	68%
MML	45	8	18	40%
Total	331	76	241	73%

[a] Phrae province (KMK = Khun Mae Kammi; WGC = Wang Chin; MMS = Mae Saroi); Lampang province (MMJ = Mae Chang; MMM = Mae Mai; TGK = Tung Kwian); Chiang Mai province (MHP = Mae Ho Phra); Lamphun province (MML = Mae Li)
[b] difference between diameter overbark (d_{ob}) measurement in forest and estimate using digitized sectional area, with a nominal critical level of 3%. Note that some trees had multiple digitized cross section height samples and thus could be counted in both difference columns and thus these two columns cannot be added meaningfully, nor are data in this table (considering only trees) and the following table (considering buttressed measuring points) directly comparable.

overestimating the adjusted data. Consequently, all subsequent taper modeling used the adjusted data at the relevant 399 points of measurement and not the original forest measurements (see Warner, 2016 and Warner et al., 2016 for detail on the taper modeling).

Table 3
Extent of buttressing at measuring points in the lower bole of sample trees identified as having buttressing.

Height up tree bole	Difference[a] in d_{ob}		Total	Percentage
	≤3%	>3%		> 3% ($n = 399$)
0.2 & 0.3 m	22	238	260	60%
0.5 & 0.6 m	43	114	157	29%
0.7 & 0.8 m	35	45	80	11%
1.3 m	0	2	2	–[b]
Total	100	399	499	

[a] difference in d_{ob} = difference between diameter overbark (d_{ob}) measurement in forest and estimate using digitized sectional area, with a nominal critical level of 3%. Note that some trees had more than one measured height with digitized buttressing, so data in this table (considering buttressed measuring points) and in the preceding table (considering only trees) are not directly comparable.
[b] less than 1%.

Discussion

A majority of trees (in particular, all the larger trees) had sectional images taken to check for buttressing in the lower bole and there were many cases where the differences were less than 3% between the image-derived diameters from the forest measurements. This indicated that the sample tree selection procedure ensured pronounced buttressing was not missed in the sampling.

The lower part of the stem is of particular interest in taper estimation because a large proportion of the commercial wood product value is located here, especially in the butt log with its larger dimensions (Robinson et al., 2011). In contrast to the current study, extreme swelling or buttressing in the lower bole have been reported to be random and of no practical significance in *Pinus sylvestris* (Pulkkinen, 2012) and to not have any major effect on the tapering of basal area (Ngomanda et al., 2012). In other studies, the stem has been regarded as circular (for example, Ojansuu and Maltamo, 1995) and this is commonly assumed (West, 2009). However, Sumida et al. (2013) excluded measurements taken below 0.3 m on the stem, as buttswell was considered to confuse the analysis of height and diameter, whereas consistent with the current results, Westfall and Scott (2010) argued that magnitude of error in the lower bole may be underestimated where only one measurement is made below breast height.

Demaerschalk (1971) reported reduced bias and reduced volume estimates when taper equations were developed after measurements over buttressing in the lower bole had been eliminated. He concluded that taper equations that did not account for this should not be used below breast height. Given this observation, perhaps of greater concern would be where taper equations were derived from a dataset where measurement below breast height had not been corrected for substantial buttressing, resulting in potential overestimates. The observations in the current study were consistent with those of Fallah et al. (2012) who noted that out-of-roundness in species of *Alnus*, *Acer* and *Quercus* was greater at the stump than at breast height. Gregoire et al. (1990) in his detailed analysis reported a relative error at breast height of about 3% when comparing the actual sectional area with that based on a girth tape measurement over buttressing. However, the error was reported to be up to more than 20% in four hardwood species by Paterson (1965) with corrections not possible using normal mensurational techniques. Parresol (1993) described a technique to estimate stump diameter where there was “fluting” by determining the largest circle or ellipse that could fit within the under bark sectional area, which would clearly underestimate the true sectional area—an issue also raised by Nölke et al. (2015). Fonweban et al.

(2011) noted that taper equations often predicted butt sections poorly, especially where pronounced buttswell was present.

Demaerschalk (1971) did suggest that large trees (presumably with an increased level of buttressing) may require additional study. However, in the current study and as was also noted by Francis (1970), pronounced buttressing (>3%) was possible in the lower bole in trees as young as 10 yr or with a breast height diameter over bark as small as 15.8 cm, indicating it is a common issue that requires addressing, at least in most teak sample tree datasets.

Practical implications

Based on the study, if a log volume were to be estimated using a teak taper equation that was based on inflated diameters due to buttressing in the lower bole (where the larger and hence more valuable logs are located), this would result in overestimating the expected log products and their value which would compound the operational difficulty of scheduling harvest yields to meet commitments and perhaps result in missing important supply deadlines to customers as well as resulting in shortfalls on projected revenue. Estimates of the amount of carbon sequestered would also be overestimated.

Substantial buttressing in the lower bole of large teak trees can result in significant errors in the estimation of the diameter at such heavily buttressed points, especially below 1.3 m from where the biggest-sized sawlogs are harvested in many mature trees. The technique developed in the current study is suggested as one that more accurately estimates the diameter in sample trees and so more truly reflects the sectional area over buttressing and any subsequent related calculations or modeling.

Conflict of interest

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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