Comparison of three tools for measuring tree diameter in stands of different age and stem size

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SUMMARY: We compared three tools (callipers, Biltmore stick and diameter tape) commonly used to measure diameter at breast height (dbh) in standing trees. Each tool works according to separate geometric relationships, operational limitations and sources of error. Two studies were devised to test each tool across a range of stand conditions. All plots in each study were measured repeatedly with each tool in a fully randomised experimental design. Individual tree diameters and time taken to measure each plot were recorded. Callipers returned consistently lower estimates of dbh compared with the other two tools across a range of tree sizes up to a mean dbh of least 55cm. Differences between tools increased with larger tree sizes. In stands with small average diameters, the maximum mean difference between the three tools was 4% of the calliper value, whereas in stands with larger diameter trees the corresponding difference was 8%. In terms of measurement times, the calliper and Biltmore stick were generally faster than the diameter tape. Where average dbh was approximately 50cm, the Biltmore stick was the fastest tool and nearly 50% faster than the diameter tape. The appeal of callipers is enhanced with the advent of affordable digital callipers and dedicated software, which streamlines data capture and analysis. However, the other two instruments are not without merit. Beyond the operational reach of callipers (commonly 65cm), the Biltmore stick may be useful where speed is a priority and the discrepancy between tools is not critical. The diameter tape is recommended where a measure that is more consistent with the callipers is required.

Introduction

Diameter at breast height (dbh) is the measurement of tree diameter at 1.3m above ground level. It is the most commonly measured attribute of standing trees in most forest regions, except in some tropical forests where trees have excessive buttressing or stilt roots (Philip, 1994). With diameter information, alone or in combination with other parameters, it is possible to estimate basal area, tree volume and stand growing stock. Diameter measurement is also important for determination of size-frequency distributions in irregular-structure stands.

The two most common tools for measuring dbh are callipers and the diameter tape. Callipers are essentially a ruler with arms that can be set on either side of the tree to give a diameter reading. Two readings are generally taken. The first is taken from the major axis (the estimated widest face) and the second from the minor axis (perpendicular to the major axis) of the tree. These readings are averaged to account for deviation from an assumed circular stem form. The diameter tape has been used for many years, especially in mature even-aged plantations (Hamilton, 1975). This tool consists of a tape that wraps around the circumference (girth) of the tree with a calibrated scale that reads in π cm units of diameter (i.e., 1cm diameter = 3.14cm on the scale).

The Biltmore stick is perhaps a less familiar instrument in the UK (Figure 1). It takes its name from the Biltmore Forestry School (USA, 1898-1913), although its use can be traced to early forest management systems in 17th century France (Brenac, 1981). It works on the principle of similar triangles and resembles a straight rule, except that the scale is non-linear. In this way it can be used to measure diameters up to 250cm using a 1 metre long stick. As with callipers the average of two measurements (i.e., major and minor axes) may improve accuracy (Husch et al., 2003). The Biltmore stick remains in use throughout eastern North America and is especially popular among foresters working in irregular-structure stands and small private woodlots.

Figure 1. Demonstration of the Biltmore stick. The operator uses lines of site to estimate tree diameter. The straight rule is deceptively simple to use, but it is important to maintain an accurate distance (usually a stretched arm length) from the operator's eye to the ruler. This particular Biltmore stick is calibrated for a reach of 64 cm. (Photo: Ian Ryding 2004)

Deriving accurate measures for dbh is not as simple as it first seems. Methley (2001) noted that inconsistencies in diameter measurement are a continuing cause of erroneous growth and yield predictions. One source of error may be due to differences between the instruments used. Moran and Williams (2002) compared all three types of tool in mixed-species stands of red oak (*Quercus rubra* L.), sugar maple (*Acer saccharum* Marsh.) and white ash (*Fraxinus americana* L.). They found significant variation in the diameter estimates made by the three tools. These differences appeared to be affected by species and tree size. The cross-sectional surface of most trees varies somewhere between circular and elliptical in form, and in many cases is highly 'eccentric' (Kellogg and Barber, 1981; Biging and Wensel, 1988) (Figure 2). The greater the deviation from a circular form, the more likely it is for there to be an under- or over-estimate of diameter. In effect, discrepancies in dbh may arise simply as a function of the operational limitations of each tool and the different geometric relationships upon which they are designed.

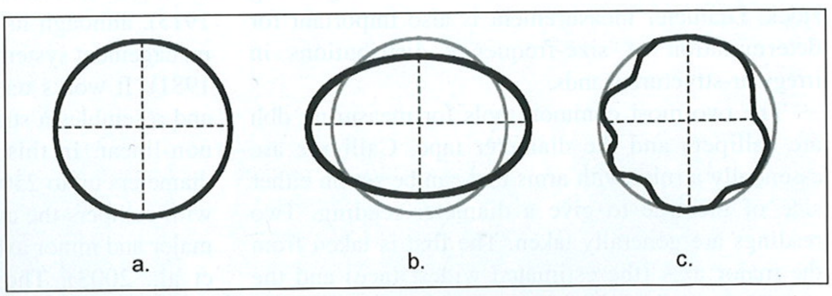

Figure 2. Diagrams of potential cross-sectional surfaces in trees: (a) circular, (b) elliptical and (c) eccentric. The potential for erroneous estimates of tree diameter increase as the cross-sectional surface deviates from circular.

Despite the importance of tree diameter in forestry, few published comparisons have been made of the relative accuracy and efficiency of the main classes of tool. In this paper, our objective was to compare the use of callipers, Biltmore stick and diameter tape in even-aged plantations of different age and average tree size. Our hypotheses were that the choice of instrument affects both the measurement of dbh and the time taken to obtain the measurement. The study does not attempt to determine the absolute accuracy of each tool, rather clarify differences between the most common tools employed in dbh assessment.

Methods

Two studies were devised to compare the relative accuracy and speed of each tool. In the first study sampling was undertaken in plots containing an equal number of closely spaced trees. The second study simulated operational inventories by assessing individual tree diameters in fixed-area circular plots in four different stand conditions. Under these conditions, the number of trees varied between plots and across sites. In both studies, individual tree diameters were recorded in addition to the time taken to complete each plot. Each plot was measured with each tool. The callipers and Biltmore stick data were

Table 1. Description of sites (stands) selected for Study 2.

Site characteristic	**Site number**			
	1	2	3	4
Location	Greystoke	Greystoke	Whinlatter	Greystoke
Species	Sitka spruce	Sitka spruce	Sitka spruce	Scots pine
Stand age (years)	12	20	35	120
Stand density (no./ha)	2532	1116	516	213
Plot area (m^2)	50	100	250	250
Mean number of trees per plot	12.4	11.2	12.9	5.3
Number of plots	12[1]	12	12	12
Stem condition	Not brashed	Partly brashed	Brashed	Brashed
Number and type of thinning	Unthinned	1 systematic	1 systematic 1 selective	>2 selective
Competing vegetation present?	Yes	No	No	Yes
Ground conditions	Grass	Dense patches of slash	Clean site	Natural regeneration in patches

[1]One plot was removed from analysis of diameter data due to a sampling problem.

based on either a single measurement (Study 1 only) or the average of two readings taken perpendicular to one another, while diameter tape data were derived from single measurements. Two sizes of callipers were used in the study; a tool with 35cm reach for small diameter stems and one with a 65cm reach for larger stems. The order in which plots were assessed, the order of measurement tool and the operator were all randomized to minimize sampling error. The order in which trees were measured within each plots was constant, making it possible to compare individual measurements between tools. All data collection took place during June 2004.

Study 1

Study 1 was located in an unthinned plantation of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (established 1976) at Greenah Crag, Cumbria. A stand was selected where trees were closely spaced (~ 1.5m) and in straight lines, thereby minimizing the proportion of total time taken to travel between trees. The majority of the trees were brashed. A total of 250 live trees were measured, in ten rows of 25 trees each. The small calliper was used in this study. The diameter of each tree and the time taken to complete each row were recorded. For the calliper and the Biltmore stick values for a single measurement and the mean of two measurements were recorded separately.

Study 2

The second study was carried out at Greystoke and Whinlatter Forests in Cumbria. Four different stands (Sites 1-4) were selected to give a range of size classes and stand densities (Table 1). Site 1 was an unthinned plantation of Sitka spruce in the early pole stage of development. Sites 2 and 3 were Sitka spruce plantations after one and two thinnings, respectively. Site 4 was characterized by large, old Scots pine (*Pinus sylvestris* L.), now managed as part of a wildlife reserve. Small patches of natural regeneration restricted access to some stems. Twelve circular plots were established within each stand (although diameter data at one plot in Site 1 was later excluded due to sampling problems). Plot centres were located at random within each stand. Plot area varied with stand density to ensure sufficient numbers of trees for statistical analysis (Table 1). The diameter of each tree and the time taken to complete each plot was recorded. The small calliper was used at Sites 1 and 2, while the large calliper was used at Sites 3 and 4.

Table 2. Mean diameter at breast height (dbh) for each combination of tool and number of measurements per tree in Study 1.

Tool	Measurements per tree	Mean dbh (cm)
Calliper	1	20.80*b*
	2	20.66*c*
Biltmore Stick	1	21.26*a*
	2	21.23*a*
Diameter Tape	1	21.00*a*

N = 250 trees per treatment. Mean values followed by the same letter are not significantly different at $p<0.05$.

Statistical Analysis

In both studies the sampling unit for diameter at breast height (cm) was the individual tree, while the sampling unit for measurement time was the mean time taken to measure each tree within each plot (in seconds). The diameter data was pooled for each tool within each stand and analysed using the paired t-test. In Study 1 there was a total of 250 trees while in Study 2 the number of trees within each stand varied from 64 (Site 4) to 155 (Site 2). The plot time data were analysed with one-way ANOVA in Study 1 and two-way ANOVA in Study 2. The analysis of time data was fully balanced with ten plots per tool in Study 1 and twelve plots per tool in each site in Study 2. Logarithmic transformation was required in Study 1 for both diameter and time data, and in Study 2 for diameter data in Site 1 and all time data. This ensured that data conformed to a normal distribution and that variances were approximately equal. MINITAB statistical software (Release 13.31) was used throughout the study.

Results

Study 1

Mean diameters ranged from 20.66 to 21.26cm, depending on the tool used and the number of measurements per tree (Table 2). Pairwise comparisons made it possible to determine systematic differences between tools and measurement protocols. The mean diameter estimate based on calliper measurements was significantly lower ($p \leq 0.01$) than for either the Biltmore stick or the diameter tape. There was also a significant difference ($p \leq 0.01$) between the two measurement protocols for the calliper, with the mean stem diameter based on two stem measurements (i.e., both major and minor axes) being 0.14cm lower than estimates based on one measurement (i.e., the major axis). In contrast, there was no difference between measurement protocols for the Biltmore stick. The overall difference between all tools and measurement protocols was less than 3% of the calliper values. The time required to measure trees was approximately 7.5 seconds per tree and there was no significant difference between tools (Table 3). No separate timings were recorded for the single diameter measurement using either the calliper or Biltmore stick, but it is likely that significant time savings would be made compared with those for two measurements per tree.

Study 2

Mean stand diameters were approximately 11, 22, 33 and 50cm at Sites 1 to 4 (Figure 3). In general, the calliper values were lowest and the Biltmore stick values were the highest within each site. Differences between these two tools were statistically significant ($p < 0.05$) at Sites 1, 3 and 4. At Site 2 there was no significant difference between all three tools. The largest absolute difference in diameter (3.8cm) was found at Site 4, where the Biltmore stick produced values that were significantly higher than those of either the calliper or diameter tape (51.86, 48.10 and 49.25, respectively). This represents a difference of at least one diameter class, assuming tree diameters are recorded in 2cm classes in most operational conditions. In relative terms, the Biltmore stick

Table 3. Analysis of variance (ANOVA) for mean measurement time per tree in Study 1 and Study 2.

Factor Effect	Degrees of Freedom	Sum of Squares	F statistic	*p*-value
a. Study 1 – One-way ANOVA				
Tool	2	0.0044	1.60	0.220
Error	27	0.0385		
b. Study 2 – Two-way ANOVA				
Tool	3	0.713	38.46	<0.001
Stand	2	0.283	22.91	<0.001
Tool x Stand	6	0.241	6.50	<0.001
Error	132	0.815		

returned diameter estimates that were 4, 3, 7 and 8% higher than for the calliper at Sites 1-4, respectively. The diameter tape generally returned estimates that were not significantly different from those of the calliper.

Differences in the mean time required to measure each tree were also recorded between tools and sites (Table 3). A significant interaction between tools and sites indicated that a variety of factors related to tree size, site conditions and operational limitations of each tool influenced the time required to measure trees. At Sites 1, 2 and 3 there was little difference between the calliper and Biltmore stick (Figure 4). Both tools were generally faster to use than the diameter tape. At Site 4, where the largest stems were measured, the Biltmore stick proved to be the fastest tool, requiring approximately half as much time as the diameter tape.

Discussion

The most important findings of this paper were that discrepancies exist between diameter readings taken by the three tools and that absolute differences increase with average tree size. For trees up to dbh of around 30cm, discrepancies between tools were small. A 3 to 4% difference in mean diameters, as was found in Study 1 and at Sites 1 and 2 in Study 2, would appear to have few implications for management. Such conditions are generally found in even-aged plantations during first and second thinning stages of development. Here the major consideration in choice of tool would be the speed of measurement. However, greater discrepancies at larger average tree sizes will be more important, especially in terms of derived variables such as basal area and tree volume. For example, an 8%

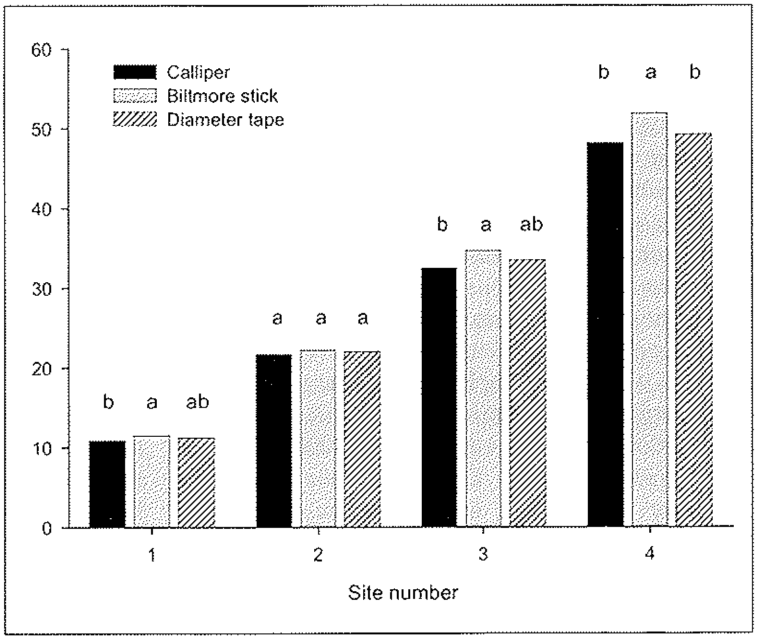

Figure 3. Mean diameter at breast height (dbh) per tree at the four sites assessed in Study 2, based on measurements made with the calliper, Biltmore stick and diameter tape. Within each stand, means diameters are not significantly different ($p<0.05$) when designated by the same letter. $n_{site1} = 115$; $n_{site2} = 134$; $n_{site3} = 155$; $n_{site4} = 64$.

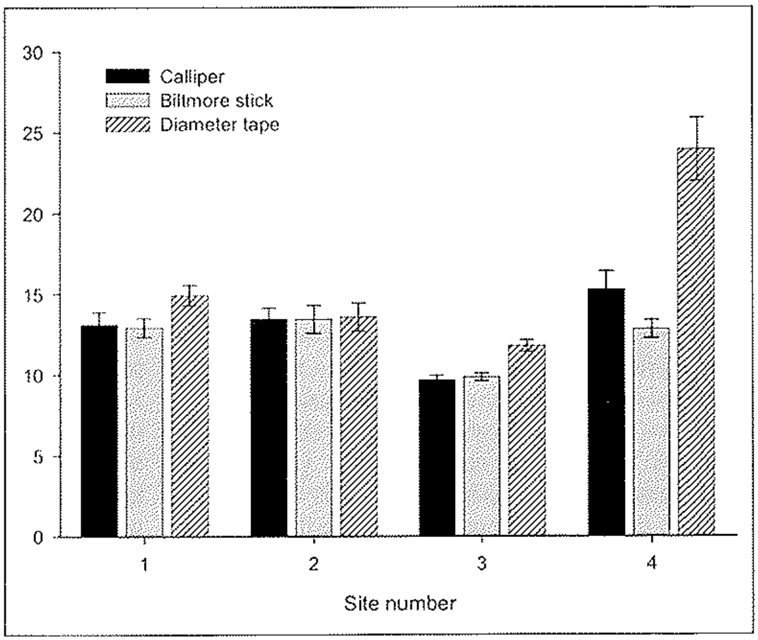

Figure 4. Mean measuring time per tree (± standard error of the mean) at the four sites assessed in Study 2, based on measurements made with the calliper, Biltmore stick and diameter tape. $n_{site1} = 115$; $n_{site2} = 134$; $n_{site3} = 155$; $n_{site4} = 64$.

discrepancy between the calliper and Biltmore stick readings for trees of around 50cm dbh, amounts to a 16.7% difference in basal area. For a Scots pine tree of 25m top height this would translate into a 0.32m^3 difference in stem volume, or 80m^3 for a stand with 250 trees/ha in this size class (Hamilton, 1975).

A second management consideration pertains to stands of irregular structure. As measurement discrepancies are not consistent across all tree sizes, inventories derived from different tools cannot be readily compared. In continuous cover forestry systems, for example, frequent diameter measurements are required in order to plan stand interventions (e.g., Kerr et al., 2002, 2003; O'Hara and Gersonde, 2004). Changing tools from one inventory to the next may introduce significant differences in estimates of basal area and growing stock, especially in stands with large diameter trees. Such errors may adversely affect estimates of standing volume and determination of basal area targets for stand interventions.

The mean diameter discrepancies found in this study are best explained in terms of different geometric relationships and operational limitations associated with each tool. In both our studies, the calliper results were consistently lower than those for the other two tools. This finding is likely related to the fact that the calliper has fewer sources of error than either the Biltmore stick or the diameter tape (Husch et al., 2003). The calliper takes direct cross-sectional readings of one or more faces of the stem. Taking and averaging multiple diameter measurements can to some extent account for irregular stem forms. In theory quadratic or geometric means will yield results with the least bias, as these account for more deviations from a circular form. In practice, Moran and Williams (2002) found that for a number of hardwood species the numerical differences between estimates based on quadratic, geometric and arithmetic means were not significant. Operational limitations with the calliper can occur when trees have not been brashed, or where there is excessive fluting of the stem. Under such conditions considerable overestimation of theoretical diameter and basal area are possible, but equally can be avoided with good field technique. Differences in Study 1 between estimates based on one and two measurement readings are evidence of the relatively high precision of this tool.

In contrast, the Biltmore stick takes indirect readings of diameter based on the principle of similar triangles. Although simple in practice, in fact, it takes a good degree of familiarity to become proficient with this instrument. As the scale is non-linear, the units of measurement become increasingly small for large diameter trees. This influences the precision and accuracy of the Biltmore stick in larger trees. The other critical factor that represents a potential source of error is the known distance of the operator from the tree (Finlayson and Tchanou, 1975). The tool itself is usually calibrated for an arm reach of 64cm, so that over- or under-reaching will lead to over- or under-estimates of diameter. In most cases, the Biltmore stick is produced with 2 or 2.5cm diameter classes. While this makes the tool less precise than the calliper, there may be operational advantages in terms of measurement speed. A single measurement with the Biltmore stick appears to be as effective as estimates of tree diameter based on two measurements (Table 2). This would likely offer significant savings in time during operational inventories, which is a major justification for use of the Biltmore stick in woodlots throughout eastern regions of the US and Canada (J. Kershaw, Pers. Comm.).

The diameter tape technique is based on the geometric relationship between circumference and diameter of a circle. Accuracy depends on the circularity of the stem and placing the tape in such a way that it avoids catching branch stubs or other stem irregularities. Since the circumference of a circle is mathematically the shortest distance to enclose any given area, any deviations from the circular form will lead to over-estimates of diameter, which in the diameter tape method are not mitigated by multiple readings.

The tests of measurement time demonstrated that the calliper and Biltmore stick were the fastest tools to use, with the Biltmore stick being the fastest instrument in measuring larger stems. The diameter tape was generally slower to use than the other tools, with the difference being most marked in measuring larger stems at Site 4 in Study 2. These differences may be partly related to the ease of use of each tool under the various stand conditions, including the presence of brash, natural regeneration and ground conditions (Table 1). With practice and 'cultural familiarity' the forester may be able to improve on the speeds reached in our study but there is always the danger of loss of accuracy. At Site 3, lower measuring speeds can be partly attributed to the clear ground conditions and cleanness of the stems. The slow speed of the diameter tape in measuring larger trees (e.g., at Site 4 in Study 2) is likely related to the average tree circumference exceeding the operator's reach. A tree with dbh of 55cm has a circumference of over 170cm, which is the maximum reach of the average adult male. If only a single measurement was made of each tree, the Biltmore stick would be the fastest tool across all tree size classes.

The calliper, which in our study produced the most conservative estimates of stem diameter, reaches its operational limits at a dbh of approximately 65cm. For measuring stands that include larger trees the options are to employ an unusually large calliper or substitute callipers with one of the other instruments. If the objective of the inventory was a quick assessment of tree size distribution within a stand, then the Biltmore stick would be an efficient 'guide' for trees up to 250cm dbh. In permanent sample plots or for research applications, however, greater precision and consistency between tools is generally required. Here the diameter tape could be used as a substitute for the callipers in very large trees, accepting that there will be a greater cost in terms of measuring time. Care would also have to be taken to ensure that the cross-sectional stem form of large trees did not deviate greatly from circular.

In conclusion, this study found that there were significant differences between tools in the estimate of tree diameter and the speed of measurement. Under some conditions, especially in larger tree size classes or in irregular-structure stands, differences between tools may be of significance in forest management. Awareness of each tool's limitations is important for the interpretation of mensuration data and the correct choice of tool for inventory and sampling work. Within its operational limits, the calliper is the most conservative tool and has fewer sources of error than the other tools. The appeal of this instrument is enhanced by the advent of affordable digital callipers and dedicated software, greatly streamlining data capture and analysis. The other tools still have their place, but care must be taken to minimise sources of error and interpretation of data, especially when dealing with large diameter stems.

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