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Assessing the Accuracy of Tree Diameter Measurements Collected at a Distance

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Abstract

The ability to measure trees remotely or at a distance may be of value to forest inventory processes. Within three forest types (young coniferous, old coniferous, and deciduous), we compared laser caliper measurements collected at distances up to 12 m from each tree, to direct contact caliper measurements. Bitterlich sector-fork measurements and diameter tape measurements were also collected for reference purposes. We used non-parametric tests to evaluate three of our four hypotheses that suggest there are no significant differences between direct and remote diameter measurements, between caliper measurements and sector-fork measurements, and between diameter measurement errors across forest types. In general, most of the differences in diameters were small (≤ 0.8 cm) and were observed within the 0–6 m measurement distance from each tree. These results suggest that forest characteristics and measurement distance may play a role in remote diameter measurement accuracy. We also performed a correlation analysis between light conditions and remote measurements. The correlation analysis suggested light conditions were not significantly correlated to diameter measurement accuracy.

Keywords: dendrometer, precision forestry, Bitterlich sector-fork, Haglöf Gator Eyes, laser caliper

1. Introduction

Examinations and tests of analog and digital tools for measuring tree diameters (dendrometers) have been reported in the literature for nearly 100 years. The main concerns associated with forest sampling procedures when using these instruments relate to accuracy, efficiency, economy, and rationality (Rhody 1975). Sophisticated instruments have been devised to measure trees from a distance or remotely (e.g. Henning and Radtke 2006) and to measure trees with special characteristics, such as fluted basal swells (e.g. Parresol and Hotvedt 1990). A range of results have been presented in comparing measurements of diameter directly obtained by using calipers or tapes. In some cases, practically no importance has been associated with the choice of instrument (Behre 1926). In other cases, the differences between two types of measurements have been very small (Krauch 1924), while others have found the differences to be statistically significant (Binot et al. 1995). Some have even suggested that the most accurate method is one that involves direct measurements of inside bark diameter (Chacko 1961). Although most dendrometers can provide estimates of outside bark diameters that are adequate for a number of field inventory applications, when minor differences between measured tree diameters have been found among dendrometers, these differences can translate into significant variations in tree volume estimates (Parker and Matney 1999).

In addition to precision dendrometers that are strapped or affixed to a tree (e.g. Yoda et al. 2000, Drew and Downes 2009), panoramic (Rhody 1975) and wide angle photography (Clark et al. 2000b) have also been tested for their ability to assist in diameter measurements. Optical sensor systems that use lasers have also been developed to count and determine the sizes of trees (Fairweather 1994, Delwiche and Vorhees 2003). A machine vision system has been recently tested that, through the detection of illuminated line segments, can count stems and determine diameters (Zhang and

Grift 2012). Further, tree diameters have been correlated with measurements obtained through the use of Lidar (Popescu 2007). Skovsgaard et al. (1998) found that remote measurements tended to overestimate tree diameters by 2 to 5%, with increasing deviations as measurement distance from a tree increased. On the other hand, Nicoletti et al. (2012) found that the two optical dendrometers tested tended to result in an underestimation of stem biomass. Williams et al. (1999) also noted that the variability of measurements increases with the distance from a tree. While the sophistication of remote methods is increasing, results generated by some of these methods can be affected by the inability of a sensor to locate blocked tree stems or measurement errors arising from stem and bark irregularities (Bell and Groman 1971).

For practical purposes, dendrometers need to be inexpensive, precise, and easy to use (Kalliovirta et al. 2005). Some efficient and reliable instruments may be expensive, complex (e.g. Parker 1997), or too heavy (e.g. Liu et al. 1995) for regular field work. Laser dendrometers might be suitable for use in practical forestry applications, yet the accuracy of the devices needs to be tested under typical operating conditions. In our case, we are interested in the ability of the laser calipers to accurately provide estimates of tree diameters from distances up to 12 m, the approximate radius of a circular inventory plot (0.04 ha) commonly used in the southern United States.

The accuracy of some types of laser dendrometers may be associated with distance from a tree, measurement time, and tree diameter. We tested three dendrometers, a diameter tape, the Haglöf Gator Eyes system mounted on an 18-inch Mantax Black caliper (when collecting diameters at a distance, remotely, hereafter called the *laser caliper*), and the Bitterlich sektorkluppe (hereafter called the *sector-fork*). A diameter tape measures the girth of a tree and estimates the quadratic mean diameter of a tree measured from all possible directions. A caliper measures the distance between parallel tangents of closed convex regions to arrive at an estimate of a diameter in a selected direction, and a sector-fork uses principles of perspective geometry to arrive at an estimate of a diameter also from a selected direction (Clark et al. 2000a). In contrast to the Laser-relascope used by Kalliovirta et al. (2005), there is no relationship between the position of the dendrometer (when in use) and a person's eye with the laser caliper; therefore theoretically, the laser caliper should be more user-friendly than other laser dendrometer devices.

As with previous evaluations (e.g. Skovsgaard et al. 1998), our study is concerned with detecting possible bias when using remote and direct (contact) instruments for measuring outside bark tree diameters. The objectives of this research were to determine the relative consistency in measurements obtained using different techniques, remotely and directly, and whether there were significant differences between these. We attempt to examine several hypotheses:

H1: There is no significant difference between direct and remote laser caliper measurements of tree diameters.

H2: There is no significant difference between caliper (direct and remote) measurements and sector-fork measurements of tree diameters.

H3: Light conditions have no significant effect on tree diameter measurements.

H4: There is no significant difference between tree diameter measurement errors for data collected in different forest types.

2. Methods

Repeated measurements are necessary for obtaining statistical stability and for assessing accuracy and precision (Bruce 1975). For this study, one hundred trees were randomly selected within each of three forest types; an older deciduous (*Quercus* spp., *Carya* spp., *Ostrya virginiana*, and others) forest (60–70 years old), an older coniferous (*Pinus echinata*, *Pinus taeda*) forest (60–70 years old), and a young coniferous (*Pinus taeda*) forest (18 years old). These three forest types had different characteristics (Table 1) and diameter distributions (Fig. 1), and thus were included in this study to assess differences with light conditions (as a function of tree density and canopy closure) and bark characteristics (as a function of tree species, as suggested by Liu et al. 2011). At the location of the study area (the University of Georgia Whitehall Forest, in northeast Georgia, USA), these are also the only main forest types present. Data were collected in the afternoon for

Table 1 Characteristics of the forested test areas

Forest type	Approximate age, years	Basal area, $m^2\ ha^{-1}$	Stem count, trees ha^{-1}	Canopy closure, %
Young coniferous	18	35.4	1,495.3	93
Old coniferous	65	22.9	303.4	85
Deciduous	65	26.2	421.7	94

12 days (4 days per forest type) during October and November 2012. Light conditions ranged between 101–60,000 lux with an average of 4,906.

We based our sample size, where the sample units were trees to measure in each of the three forest types, as a compromise between time availability and estimated precision of the population mean. Of primary interest to us was the difference between the direct caliper measurement and the other measurements made with the caliper at a distance. The computation of the deviation in diameter values, DEV_{idj}, or the deviation between the direct measurement and the measurement made for tree *i* at distance *d* in forest type *j*.

$$DEV_{idj} = DBH_{i0j} - DBH_{idj} \tag{1}$$

DBH_{i0j} represents the direct caliper measurement for tree *i* in forest type *j*. DBH_{idj}, which could either be smaller or larger than DBH_{i0j}, represents the caliper measurement for tree *i* in forest type *j*, collected at distance *d*. After collecting 100 samples, the standard deviation of these values was computed to determine whether the sample size was appropriate. The standard deviation for each forest type (*j*) and each distance (*d*) was thus computed using the following formula:

$$s_{dj} = \left(\frac{\sum_{i=1}^{n}\left(DEV_{idj}^{2}\right) - \left(\frac{\sum_{i=1}^{n}\left(DEV_{idj}\right)^{2}}{n} \right)}{n-1} \right)^{0.5} \quad \forall d, j \tag{2}$$

We assessed the sample size required for each distance and forest type (n_{dj}), assuming a desired 95% confidence interval, using the following sample size formula,

$$n_{dj} = \left(\frac{1.96\, s_{dj}}{E} \right)^{2} \tag{3}$$

where s_{dj} represents the standard deviation for deviations in values found at distance *d* in forest type *j*. The value *E* represents an assumed objective for estimating the population mean deviation in values between direct measurements and measurements collected at a distance (i.e. to within a certain number of units, represented by *E*). When we assumed an objective of estimating the population mean deviation to be within

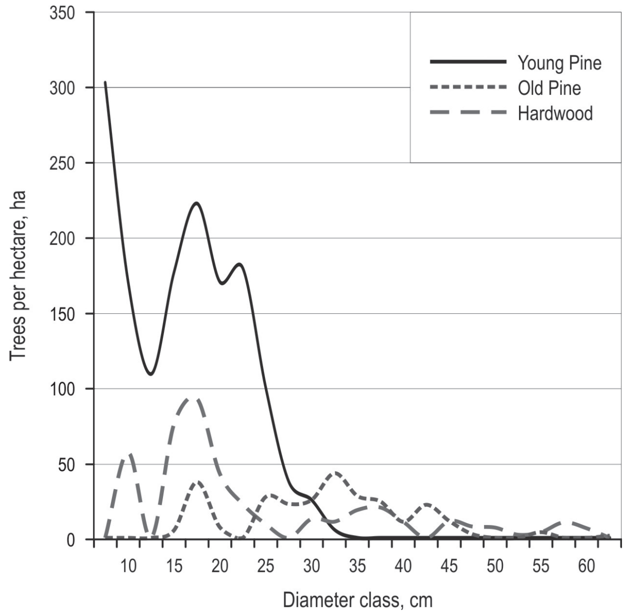

Fig. 1 Diameter distributions of the young coniferous, older coniferous and deciduous test areas

0.15 cm, we found that 100 samples was sufficient. This assumption (0.15 cm) was at worst, about 33% of a single standard deviation representing the difference in direct and remote measurements. In only one case (the deciduous forest at the 12 m distance) was the suggested sample size larger than 100 trees (102 trees). This sample size (tree count) was also consistent with other recent work in the southern United States (Parker and Matney 1999, Liu et al. 2011).

In all cases, the selected trees were measured along their stem to collect the diameter at breast height (*DBH*) outside bark at 1.37 m above ground. We used masking tape to mark the location just below where *DBH* would be measured so that measurements would all be made at the same place on each tree at the edge of the actual bark. Each tree was visited one time during the study period to collect all seven diameter measurements. Three measurements involved directly touching each tree (diameter tape, sector-fork, and Mantax Black caliper), and the other four involved single remote measurements of *DBH* with the laser caliper along a consistent line of sight from the tree at 3 m, 6 m, 9 m, and 12 m (Fig. 2). These distances from each tree were marked on the ground with wire stake flags. The sector-fork and direct (0 m) caliper measurements were also made along this same line of sight. Measurements were made in order of diameter tape, sector-fork, 0 m, 3 m, 6 m, 9 m, and 12 m caliper measurements. This was to ensure efficient use of field

Fig. 2 Remote measurements conducted with the laser caliper dendrometer

time and consistent measurement collection. For this study, the direct caliper measurement was assumed to be the best or the »true« diameter. We allowed up to 30 seconds for each individual remote caliper measurement. The diameter tape measurements were collected for reference purposes, as this is a common method used in the southern United States. Measurements made using diameter tapes have been shown to be different than those collected using calipers (McArdle 1928), and technically should not be directly compared to single caliper measurements or sector-fork measurements given the irregular shape of most tree boles (Brickell 1970, Moran and Williams 2002). However, for illustrative purposes, we make those comparisons in this study.

Fig. 3 Light conditions being measured using the Mastech LX1330B light meter

While a variety of electronic dendrometers and scanning systems are available, due to availability, time, and cost limitations, only the Mantax Black caliper was chosen for testing. For the same reasons, all of the measurements were collected by one individual after several hundred practice measurements with both the sector-fork and the laser caliper, and after practice on fixed width, non-natural targets. This process helped avoid differences between individuals, although they could be small (Elzinga et al. 2005). The only environmental variable that was collected with the sampling of each tree was the incident light luminous emittance (lux) using a Mastech LX1330B light meter (Fig. 3). This lux data were collected to determine whether light conditions are correlated with remote diameter measurement accuracy.

Errors in successive measurements of tree diameters can occur with some instruments, and may be due to the following (McCarthy 1924, Robertson 1928):

⇒ misjudging points of successive measurements;
⇒ failing to place the instrument in its proper plane;
⇒ measuring within close proximity to tree deformations;
⇒ failing to account for differences in the tension of bark on trees;
⇒ misreading instrument divisions;
⇒ failing to notice weathering and scaling of tree bark;
⇒ failing to know that instruments can be out of adjustment.

To limit potential errors such as these, we developed a set of standard methods for data collection. These methods included measuring the diameter of a tree all seven times with each visit, using the same person to collect all of the measurements, and conducting six of the seven measurements from the same perspective with respect to the tree; the exception involved the use of the diameter tape. The caliper tongs were also closed after each measurement to avoid biasing subsequent measurements.

While direct caliper measurements can be subject to error described by Abbé's Principle, remote caliper measurements will not (Clark 2003). This principle states that measurement errors with calipers will increase as the object being measured moves away from the caliper bar, causing the caliper's tongs to bend outward, which introduces error. To minimize this problem when using the caliper to make direct measurements of tree diameters, the bole of the tree was placed as close as possible to the caliper bar, which reduced the bending force on the tongs. When larger trees were measured, this type of error could be introduced when pressure from the tree bole was placed further out on the tongs. We did not employ a correction factor in these instances, and given that the caliper is relatively new, we assumed that the forces acting on the tongs, perhaps requiring them to bend outward rather than to slide naturally along the caliper bar, would be minimized.

Ideally, the set of laser caliper measurement deviations for a specific distance *d* (direct measurement – distance *d* measurement) in a forest type *j* should be normally distributed around zero (no deviation). However, the ability to place the laser lights exactly on the edge of each tree at exactly the same time was difficult, perhaps due to a combination of general light conditions, bark conditions (wet, dry, fragmented, etc.), and shadows within the crevasses of the bark. While we tested the correlation between accuracy and general light conditions, the other potential factors were not tested. We used BestFit software (Palisade Corporation 1996) to test whether each set of laser caliper measurement deviations for a specific distance *d* was normally distributed. In 10 of the 12 cases, sets of deviations were not statistically significant with respect to their ability to represent a normal distribution, according to Chi–squared, Anderson-Darling, or Kolmogorov-Smirnov tests. Therefore, a non-parametric method, Wilcoxon's matched-pairs signed-ranks test, was used to determine whether pairs of sample sets arose from the same population having the same location. Another non–parametric method, the Mann-Whitney test, was used to determine whether unpaired data of sample sets from different forest types had significantly different median values. When applying the Wilcoxon's matched-pairs signed-ranks test, if the rank sums of the paired samples are approximately the same, we would expect that they are not significantly different (Sokal and Rohlf 1995). Although we initially assumed they are different, we applied this test to assess the difference between diameter tape measurements and other direct measurements. In applying this test for an analysis of Hypothesis 1, the test statistic was the tree diameter, and we compared the remotely obtained caliper measurements (3–12 m) to the direct caliper measurement (0 m) within each forest type. In applying this test for an analysis of Hypothesis 2, the test statistic was again the tree diameter, we compared the sector-fork measurements to all caliper measurements (direct, 3–12 m) within each forest type. In assessing Hypothesis 3, Pearson's product-moment correlation coefficient was computed to estimate the linear correlation or association between illuminance (lux measurements at *DBH*) and the deviations computed for remotely measured tree diameters using the caliper (direct measurement – remote measurement). Both the actual deviation (positive or negative value) and the absolute value of the deviation were assessed in this correlation analysis. The aim was to determine whether the Pearson product-moment correlation coefficient was significantly different from zero at the $p = 0.05$ level. In other words, if the associated *p*-value for each pair of data was less than 0.05, then the Pearson product-moment correlation coefficient was considered significantly different from zero. For Hypothesis 4, we focused on measurements collected at a specific distance from each tree (e.g. 3 m), and attempted to determine whether the unpaired sample data (the diameter deviations) from the three different forest types were significantly different. Here, the Mann-Whitney test was employed to determine whether the median value of the deviation in diameters was significantly different among the three forest types.

3. Results

The average diameters measured within each forest type and the associated measurement process are shown in Table 2. In general, tree diameters estimated using the diameter tape were significantly greater ($p < 0.05$) than measurements of diameters estimated using other methods. However, the other methods only considered one viewing perspective of a tree, thus do not fully account for irregularities in the shape of tree boles. The general pattern of results within a forest type is similar, yet the use of the sector-fork consistently produced a lower mean diameter when compared to the other measurements. Table 2 also provides a measure of variation (standard deviation) among the sets of diameters, reflecting the fact that there is more diversity among tree sizes in the deciduous forest than in the two coniferous forests. Interestingly, 12 m remote caliper measurements were consistently slightly smaller with regard to the standard deviation than diameter measurements collected with the other processes.

Since the diameter distribution of trees within each forest type is different, another way to view the results is to compare the deviation in diameters with respect to the 0 m caliper measurement (Fig. 4). In general, most of the deviations were 0.8 cm or less for individual trees. There are two interesting results here; first, the remote measurements 9 m and greater within the young coniferous stand tended to overestimate tree diameters, and second, the sector-fork measurements across all forest types tended to slightly underestimate tree diameters. The measurement deviations

Table 2 Mean tree diameter and standard deviation of tree diameters by forest and measurement type

Sample measurement	Young coniferous		Old coniferous		Deciduous	
	Mean, cm	SD*, cm	Mean, cm	SD*, cm	Mean, cm	SD*, cm
Diameter tape	18.36	4.87	34.64	8.42	30.11	14.04
Sector–fork	17.88	4.68	33.74	8.62	29.50	13.69
Caliper – 0 m	18.03	4.79	34.35	8.52	29.79	13.98
Caliper – 3 m	18.07	4.72	34.34	8.52	29.56	13.77
Caliper – 6 m	18.11	4.68	34.35	8.45	29.69	13.75
Caliper – 9 m	18.24	4.63	34.34	8.41	29.67	13.63
Caliper – 12 m	18.31	4.56	34.26	8.38	29.68	13.56

* Standard deviation

also suggest that the use of the sector-fork tended to result in a noticeably larger amount of variation across forest types. In general, the variation in caliper measurement deviations (as compared to the 0 m caliper measurement) tended to increase slightly the farther one moved away from the tree.

When examining the differences between the direct caliper measurement and the remote caliper measurements within the deciduous stand, we reject the null hypotheses ($p < 0.05$) that samples obtained at 3 m, 6 m, and 9 m from each tree are the same as the direct measurement. However, the 12 m remote measurements ($p > 0.05$) were not significantly different from the direct caliper measurement. Therefore, in assessing Hypothesis 1, we found mixed results from measurements collected in the deciduous stand. When examining the differences between direct and remote caliper measurements within the older coniferous stand, there are no statistically significant ($p > 0.05$) differences between the direct and remote measurements. Therefore, we could not reject the null hypothesis that the samples arose from the same population. The same can be said about the direct and 3 m remote measurements obtained from the young coniferous stand. However, measurements obtained from 6–12 m were statistically significantly different than the direct measurement ($p < 0.05$); therefore, we reject the null hypothesis in these cases.

In comparing the caliper measurements to the sector-fork measurements, we found no statistically significant differences ($p > 0.05$) in the deciduous stand. For the older coniferous stand, we found statistically significant differences between the sector-fork measurements and the direct caliper and 3 m caliper mea-

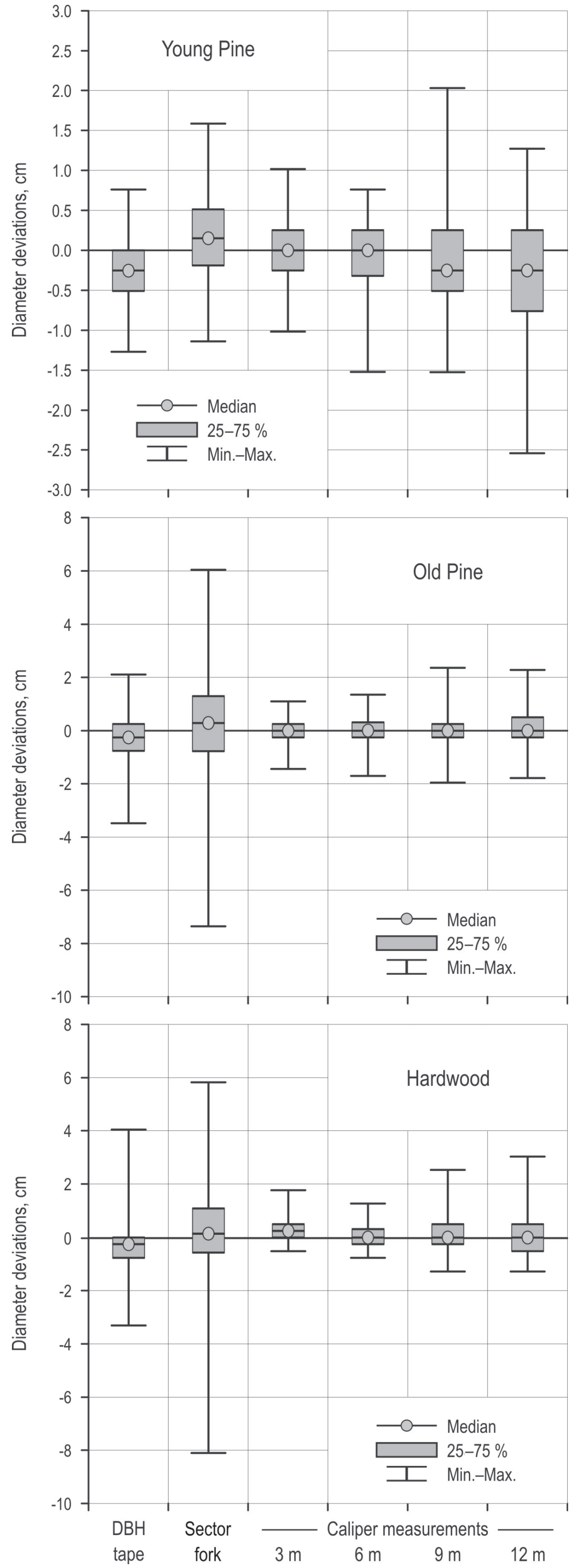

Fig. 4 Box-and-whisker plot of the deviation in tree diameters when compared to the 0 m (direct) caliper measurements

surements ($p < 0.05$); all other comparisons of diameters collected remotely in the older coniferous stand with the calipers were not significantly different than the sector-fork measurements. According to the results obtained from the application of the Wilcoxon two-sample test, the sector-fork data collected within the young coniferous stand were considered statistically significantly different ($p < 0.05$) than the data collected at all distances with the calipers.

The correlation analysis between illuminance (lux) and the deviation in remote caliper measurements from direct caliper measurements indicated very weak relationships in many instances (Table 3). In this analysis the deviation could be either positive or negative, and therefore it is assumed that light characteristics may force an overestimate or underestimate of the tree diameter when measured remotely. However, based on the *p*-values of this analysis, illuminance was not significantly correlated with the deviation in diameter measurements between the direct measurement and the remote measurements. We also assessed the correlation between illuminance and the absolute value of the difference between remote caliper measurements and direct caliper measurements, assuming that the direction of the deviation (either an overestimate or underestimate of the tree diameter) was not necessarily forced by illuminance, but that changes in illuminance simply caused a deviation one way or the other (Table 4). As with the prior analysis, it did not appear that illuminance was significantly correlated with the absolute value of the difference between remote caliper measurements and direct caliper measurements based on the *p*-values ($p > 0.05$) produced.

Table 3 Pearson's product-moment correlation (r_{xy}) between illuminance (lux) and the deviation in remote caliper measurements from direct caliper measurements

Sample distance	Young coniferous		Old coniferous		Deciduous	
	r_{xy}	*p*-value	r_{xy}	*p*-value	r_{xy}	*p*-value
3 m	0.126	0.213	0.024	0.810	0.042	0.678
6 m	0.074	0.467	–0.070	0.486	–0.062	0.540
9 m	0.092	0.364	–0.021	0.833	–0.103	0.310
12 m	0.075	0.456	–0.008	0.939	–0.117	0.247

In assessing differences between forest types, using the Mann-Whitney non-parametric test and the deviations between direct and remote measurements as the test statistic, at 3 m we found that there were significant differences between the deciduous stand and both coniferous stands ($p < 0.05$), yet there was no significant difference between the young and old coniferous stands. When using the absolute value of the deviation as the test statistic, no significant differences were observed. In comparing the 6 m remote measurements, the only significant differences ($p < 0.05$) were observed between the deciduous and young coniferous stands. When the absolute value of the deviations were used as the test statistic, significant differences ($p < 0.05$) were only observed between the deciduous and old coniferous stands, interestingly. There were two significant differences in the 9 m measurements among forest types: between the young coniferous and old coniferous stands, and between the young coniferous and deciduous stands. However, when the absolute value of the deviations was used as the test statistic, no significant differences ($p < 0.05$) were observed. Similarly, these same results were observed with the 12 m measurements. In sum, when comparing measurements collected from the same distance away from a tree, yet within different forest types, when the absolute value of the measurement deviations were compared, in only one case was there a significant difference. And when using the original (positive and negative values) measurement deviations, the results were mixed, but when comparing the longer distances there seemed to be differences between the measurement of small trees (young coniferous stand) and the measurement of larger trees (deciduous and old coniferous stand).

Table 4 Pearson's product-moment correlation (r_{xy}) between illuminance (lux) and the absolute value of the deviation in remote caliper measurements from direct caliper measurements

Sample distance	Young coniferous		Old coniferous		Deciduous	
	r_{xy}	*p*-value	r_{xy}	*p*-value	r_{xy}	*p*-value
3 m	0.048	0.636	0.045	0.659	–0.013	0.897
6 m	–0.100	0.322	0.101	0.319	–0.027	0.792
9 m	–0.076	0.455	–0.077	0.444	–0.057	0.573
12 m	–0.108	0.286	–0.113	0.264	–0.004	0.971

4. Discussion

The ability to remotely measure the diameter of trees has practical value for field technicians in that travel time to individual trees at sample locations can be reduced. Further, upper-stem diameters necessary to understand the extent of merchantability within a tree can be estimated more reliably, as these otherwise generally are ocularly estimated. Perhaps the efficiency of data collection processes can be increased, however, the efficiency of using laser calipers to measure tree diameters remotely was not assessed in this research. We found significant differences in diameters measured using a diameter tape and using the calipers. We recognize that it is commonly accepted that diameter tape measurements will more likely lead to different results than caliper or sector-fork measurements, due to variations in tree bole and bark shape (McArdle 1928). Two or more sector-fork or caliper measurements acquired from different perspectives of the tree bole can alleviate some of these concerns. However, in this work we assumed that only one direction (or perspective) of a tree bole would be used in conjunction with the laser calipers. This assumption arises from the notion that a field technician should be able to stand in the middle of a circular measurement plot and use the laser calipers to remotely measure all of the trees in the plot without having to move away from the plot center. We further only measured tree diameters with the sector-fork from one perspective in order to be consistent with, and comparable to, the laser caliper measurements. These limitations in measurement standards do not detract from the practical value of collecting remote measurements, and associated decisions were made to accommodate the study design.

In our work, we did find that the use of the sector-fork resulted in greater variation among the deviations from the direct (0 m) caliper measurement conducted at the same point on a tree and viewed from the same perspective. In fact, on average, the sector-fork diameter measurements were slightly smaller than the caliper measurements. We attribute a great deal of this problem to the scale of each device. Cummins (1937) found that differences in scale between instruments can contribute to differences in diameter measurements. The calipers have a graduated scale in 0.25 cm (0.1 inch) increments, yet the sector-fork scale has a graduated scale in 1 cm increments, and diameters were estimated to the nearest 0.5 cm. The scale on the sector-fork is also non-linear, and larger diameter measurements seemed to be more difficult to refine, while the caliper scale is linear and consistent.

One issue that could have potentially introduced error into the measurement of tree diameters with the laser calipers was the ability of the person performing the measurements to consistently measure a tree diameter at the same height and same angle (horizontal or vertical) to the tree bole. The calipers, while not overly heavy (in terms of weight), needed to be held steady for 10–20 seconds each time a diameter was measured. If fatigue sets in after numerous repeated measurements, this practice can become a burden on the field technician and possibly affect the quality of results. Further, any uncertainty on behalf of the field technician regarding where the tree diameter should be measured can affect the person's ability to position the laser points correctly on the edge of a tree bole. The extra time required to ensure the correct position of the laser points on a tree bole could affect the increase in efficiency expected when using a remote instrument, and perhaps lead to greater error. Therefore, one drawback to our analysis was the time limit we placed on measuring diameters when the calipers were used remotely. While effort was made to apply similar amounts of time at each stage in the measurement collection process, there may have been an association between measurement time and measurement accuracy of which we are unaware.

Another issue that may have introduced error during the measurement process was distraction on behalf of the operator of the equipment. One particular distraction was glare caused by the Sun. At times, depending on the arrangement of the field technician, the tree, and the Sun, the laser points were difficult to see on the edges of tree boles. Although the field technician practiced using each device for several weeks prior to the onset of the study, not all environmental factors could be replicated during the practice period. This potentially introduced error into the analysis. Further, we did not design the study to control for stem density or understory vegetation composition or density. Each set of 100 samples was contained within one of three stands, represented by one of the three forest types, and conditions within each stand (density, understory) were very similar. We recognize the fact that stem density and understory vegetation composition can play a role in the ability of a person to accurately measure tree bole diameters with a laser caliper, and the slight variations in these that were evident at the study site could have potentially introduced error into the analysis.

One issue we discovered through a review of the literature was that over the course of a study period (and even over the course of a day) tree diameters may change slightly due to cambial growth, water balance, or due to the angle from which the remote measurements were made (Haasis 1934, Pesonen et al. 2004, Devine and Harrington 2011). Paired comparisons in our analysis were made with measurements that were collected within about five minutes of each other during each visit to a tree; therefore, this issue should have been minimized through the study design. We also understood that there may be some aspects of tree and understory vegetation, bark color, stem density, and forest type in general that could cause error and affect the ability to distinguish bark edges with a high level of accuracy. For example, slight variations in tree or bark condition could act to misguide a field technician into collecting remote measurements that do not necessarily represent the true edge of a tree bole. Tree lean and the shape of a tree's cross-sectional area may have also contributed to the variations in measurements between instruments (Grosenbaugh 1963). The differences between forest types with respect to these types of issues appear to be most pronounced at distances of 6 m or less to the target tree, after which there are no significant differences in remote measurements. Thus the viewing perspective (i.e. being too close to the measured object) may be a concern.

In summary, even while there were significant differences in diameters measured using a diameter tape and using the calipers, due to variations in tree bole and bark shape, these differences were, on average, 0.55 cm or less in each of the three forest types related to this study. In most cases of the distances from the subject tree, this represents a 2% or less deviation from the diameter estimated using a diameter tape. The differences among average forest caliper measurements of tree diameters, from 3 to 12 m distances, are also less than 0.3 cm. Therefore, the usefulness of the laser caliper system for measuring tree diameters within the forest conditions represented by this study seems good for distances up to at least 12 m. However, trees within measurement plots that have easily accessible boles from the center of the plots may be more efficiently measured using traditional methods (diameter tape, sector fork). In addition, it would seem necessary to measure the distance from a plot center to a borderline tree (situated on a plot edge). If this is necessary, these trees may also be more efficiently measured using traditional methods rather than remote methods, since the technician will likely be in physical contact with the tree when measuring its distance from the plot center. This of course assumes that remote instruments (laser rangefinders) are not employed to measure distances.

5. Conclusions

Tree diameters are one of the main components of forest volume estimation processes. Assuming the same level of sampling intensity with and without remote measurements of tree diameters, if remote measurements can accurately represent forest conditions, management costs can possibly be reduced. While laser caliper measurements were only collected with respect to one viewing perspective of a tree, they were consistently smaller on average than diameter measurements collected with a diameter tape. While it seemed that most of the significant differences in remote measurements were observed within the first 6 m of trees, these differences were rather small (0.8 cm or less for individual trees). The direction of the difference (over or under the direct caliper measurement) was different for each forest type, which if consistently observed, might suggest the use of a small correction value for each type of forest measured. However, reasonably accurate remote measurements may be attractive to field personnel for the time saved not having to travel to and physically touch each tree. While significant differences were found, the small differences found in this study may not have a significant impact on in field practices when tree diameters are grouped into one–inch diameter classes, as they often are in the southern United States. The laser calipers are able to provide accurate diameter readings at a distance within 12 m, and measurements that are traditionally collected remotely (e.g. upper stem diameters, or lengths of the merchantable portion of a stem) can perhaps be estimated or measured more accurately.

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