

Partial Resistance Drilling to Assess Wood Density in Trees

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Abstract

Increment core analysis has dominated research for more than half a century and has been used as a standard method for assessing basic wood density in forests, for determining biomass of ecosystems, and for investigating climate history through dendrochronological analysis. Comprehensive wood density models have been developed for commercially important species that use outer wood cores and knowledge of internal wood density distribution to fairly accurately predict the density of major tree components. With the development of SilviScan and near infrared spectroscopy instruments, more wood and fiber properties can be obtained from a single increment core sample, allowing comprehensive wood quality evaluation of plantation trees for genetic improvement, forest management, and optimal wood utilization. However, for many users or in many applications, increment core sampling and subsequent laboratory analysis are time-consuming and expensive. A rapid field-type nondestructive method is needed in various research programs and forest operations. This report provides an in-depth review of the traditional increment coring method and the more recent electronic resistance drilling technique for assessing wood density of trees. This report also proposes a new concept of partial resistance drilling for more efficient and economical collection of wood density data in the forest.

Keywords: amplitude, friction, increment core, Resistograph, resistance profile, wood density

Introduction

Density is one of the important wood characteristics of standing trees that affects the properties and performance of various wood products, such as sawn timber, reconstituted products, and pulp and paper (Gao et al. 2017). Wood density has been considered a quality trait in tree improvement programs because of its economic value and high degree of genetic control (Sprague et al. 1983); it is a fundamental component of biomass determinations in ecosystem studies and is a cornerstone of functional trait analysis in community ecology (Wiemann and Williamson 2013). Wood density is highly variable, particularly within and between individual trees in forests. The within-tree variation constitutes a major part of the overall variability and has been well-documented for some commercial species (Kandeel and Bensend 1969, Wiemann and Williamson 2014, Tian et al. 1995, Kimberley et al. 2015).

The traditional technique for determining wood density in standing trees is to extract increment cores from trees and measure their volume and mass of wood in a laboratory. Although this method is relatively easy and accurate, it is time-consuming and labor-intensive for wood quality surveys or genetic improvement programs that require extensive density analyses. Even so, since its invention in the mid1800s (Pressler 1866), the increment borer has been the primary tool for “nondestructive” sampling of standing trees.

Another technique capable of providing highly accurate wood density measurement is x-ray densitometry. This technique also uses increment cores. Advantages of this technique are its ability to clearly obtain

wood density values in different biological zones and allow for densitometry comparisons between radii within the same tree, between trees on the same site, and between mean density values at different sites (Cown and Clement 1983, Eberhardt and Samuelson 2015). However, the x-ray method requires careful sample preparation and data analysis and can only be carried out in the laboratory. It does not satisfy the requirements for a rapid and economical evaluation of wood density in standing trees.

For the purpose of achieving rapid, reliable, and economical wood density measurements in standing trees without using increment borers, a field-type nondestructive method is needed in various research programs and forest operations. In a recent publication, Gao et al. (2017) reviewed world-wide research development in the use of several field nondestructive methods for rapid determination of wood density in trees and discussed pros and cons of each method for field applications. This report provides an in-depth analysis of the capability of increment borer and electronic resistance drilling tools and proposes a new concept of partial resistance drilling for more efficient and economical collection of wood density data in trees.

Increment coring

For many years, the increment borer has been used as a simple nondestructive tool to evaluate wood quality of forest resources. The tool was originally developed in Germany ca. 1855 (Pressler 1866) and has changed little since its original design (Grissino-Mayer 2003). Figure 1 shows an increment borer being used to extract a core sample from a standing tree at breast height. An increment core can provide a complete wood sample if it stretches from the pith to the bark and is only limited by the length of the borer and one's ability to extract an adequate core. Borer diameters range from 4 to 12 mm, with the larger diameters giving the best samples when larger quantities of wood are required (Jozsa 1988, Grissino-Mayer 2003, Williamson and Wiemann 2010). Larger diameter borers (12 mm) cause less compaction because the area to volume ratio of the wood sample is smaller, and larger samples are easier to measure. However, larger diameter borers require disproportionately greater expenditures of energy to extract cores. Therefore, limiting the depth of penetration to only that required to obtain an adequate sample is desirable. For most purposes, it is desirable to bore in a radial line to the pith. This is sometimes difficult because trees aren't perfectly round and human operation error may cause the core to be off center.



Figure 1. Increment borer being used to extract a core sample from a standing tree at breast height.

Reliable estimates of tree density are derived from cores that extend from bark to pith because they reveal the full extent of radial variation. Unfortunately, boring trees from bark to pith is often difficult and replete with problems. Some of the challenges encountered by foresters and dendrochronologists are (1) trees are too large for the borer to reach the pith; (2) the borer misses the pith, passing to the side of it; (3) borers are difficult to insert in trees with dense wood; and (4) borers are difficult to extract, for multiple reasons (Maeglin 1979, Jozsa 1988, Grissino-Mayer 2003).

Wiemann approximation

Given the problems of bark-to-pith boring, alternative partial sampling techniques have been developed for estimating tree density even when radial variation is substantial. Wiemann and Williamson (2012) suggested a novel approach, based on stem geometry, to sample only the wood that approximates the density of a whole disk. The concept is that, if a function describing the radial variation in density is known, then it can be used to determine the point along the radius at which the wood density equals the area-weighted density. In theory, the tree need only be bored to that point, termed the Wiemann approximation, to estimate density of the whole cross section. For radial changes that are linear, the point of approximation falls at two-thirds of the wood radius; that is, the wood density at two-thirds of the distance from pith to bark should equal the density of the whole disk (Wiemann and Williamson 2012). In application of this method, the point one-sixth of the diameter inward from the bark–xylem interface would be used to correspond to two-thirds of the distance from the pith outward. This method has been proven successful for trees with linear (or no) changes in density across the radius (Wiemann and Williamson 2012, 2013). The usefulness of the method for estimating wood density of a species is conditional on knowledge of the pattern of radial change in density and the degree of eccentricity in the species.

Outer wood density approach

Increment coring is by far the most widely used sampling technique to obtain wood density information in standing trees. Knowledge of within-tree patterns has allowed the use of outer wood values for stem selection in breeding programs and for preharvest assessments (Cown 2006, Kimberley et al. 2015). In New Zealand, extensive wood density surveys were carried out on radiata pine (*Pinus radiata* D. Don) resources by extracting partial cores at breast height. The survey results indicated a good relationship between outer wood density and whole-tree density. An empirical model called STANDQUA was developed in the mid1990s that enabled within-tree patterns of radiata pine wood density to be estimated from breast-height core samples and the future log-level wood density to be predicted (Tian and Cown 1995, Tian et al. 1995). More recently, comprehensive wood density models were developed for radiata pine using an extensive wood density dataset (from breast-height increment cores and stem disks) collected during 50 years of research to predict within-tree, within-stand, and among-stand variation in wood density (Palmer et al. 2013, Kimberley et al. 2015). For instance, the breast-height wood density of radiata pine was found to show a monotonic increase with increasing ring number from the pith, with the rate of increase diminishing after approximately 20 rings from the pith (Fig. 2). Along a tree stem, whole-disk average density showed a sigmoidal pattern with relative height well-approximated by a cubic function (Fig. 3). These models can be used to predict the density of disks or logs cut from any position within a tree and can use measured outer wood density values to predict the density, by log height, for a particular stand. It can further be used in conjunction with outer wood density to predict wood density distributions by logs for stands of any specified geographic location and management regime (Kimberley et al. 2015). Many forest growers in New Zealand today routinely collect breast-height outer wood cores as part of their preharvest assessments.

Compared with the traditional destructive sampling method of cutting disks, the use of an increment borer to extract trunk tissue is considered an economically viable option to minimize the work load. In addition,

increment cores allow specific biological zones (for example, the inner 10 rings or the outer 10 rings) to be identified for study and ensure valid comparisons when properties vary with tree age. However, increment coring will always have potential to damage the trunks of the cored trees and incur some risk of negative impacts on tree health. For example, boring in a veneer quality black cherry tree will lower the value of the butt veneer log and is therefore considered destructive. Also, bore holes can be the entrance source for decay and disease (Hart and Wargo 1965). In addition, for many applications such as tree improvement programs and large-scale wood quality studies, in which potentially hundreds and even thousands of trees must be sampled for wood density information, increment coring is still time-consuming and expensive. A rapid field-type nondestructive method is becoming increasingly important for various research programs and forest operations.

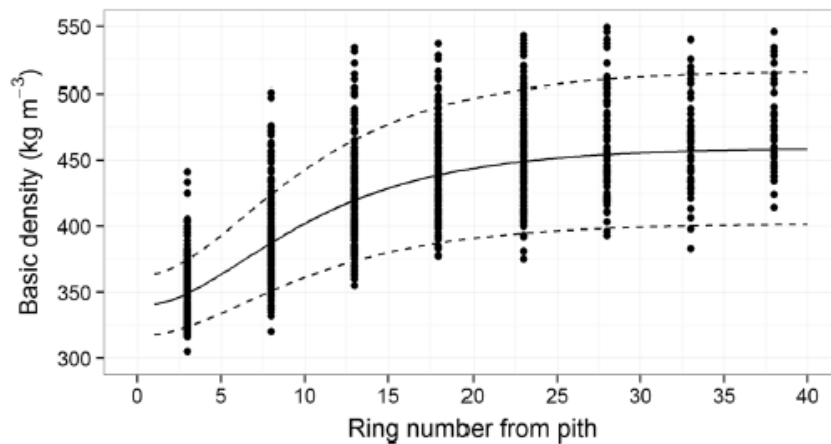


Figure 2. Pith-to-bark radial trend in breast-height wood density. Black dots correspond to mean densities by a five-ring group at each site. The black lines show density predicted by model 1 for an average site (middle solid line, $L = 0$) and for sites at the 5th and 95th percentiles (lower and upper dashed lines, $L = -34.6$ and $L = +34.6$, respectively) (Kimberley et al. 2015).

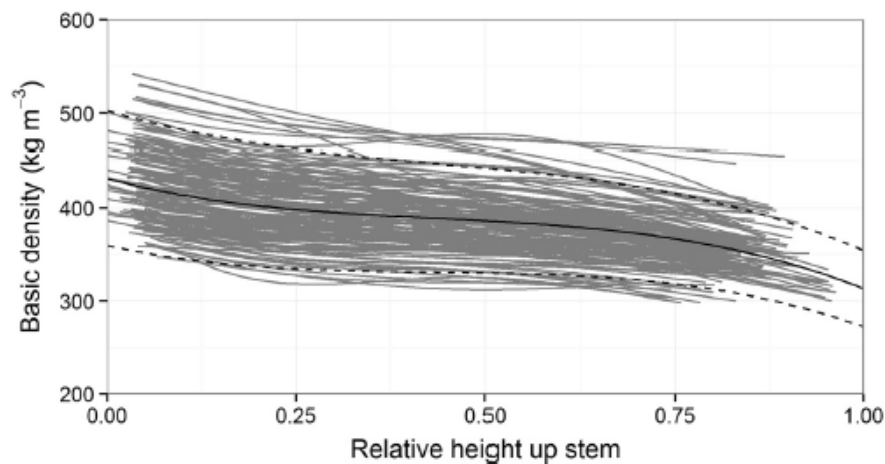


Figure 3. Variation in whole-disk density with relative height up the stem. The grey lines are smoothing curves fitted to the disk densities from each of 150 sites. The black lines show disk density predicted by model 3 for an average site (middle line, $L = 0$) and for sites at the 5th and 95th percentiles (lower and upper dashed lines, $L = -59.3$ and $L = +59.3$, respectively) (Kimberley et al. 2015).

Resistance drilling measurement

The resistance drilling tool is a mechanical drill system that measures the relative density profile as a rotating drill bit is driven into wood at a constant speed. Figure 4 shows the use of a resistance drill (Resistograph, Rinntech, Heidelberg, Germany) in a standing tree to obtain the relative resistance profile. The technique operates on the principle that drilling resistance (torque) is directly related to the density of the material being tested (Rinn 1988, 1989, 1990; Rinn et al. 1996). During the process of a drilling measurement, the relative drilling resistance, feeding force, and speed parameters can be measured continuously as a function of the drill bit position in the drilling path. A resistance drilling tool typically consists of a power drill unit, a small-diameter spade-type drill bit, and an electronic device that can be connected to the serial interface input of any standard personal computer. As the drill bit moves through the wood in a linear path, the penetration resistance along its path is measured and recorded. The pattern of change in relative resistance is recorded as a digital representation display.



Figure 4. Electronically regulated resistance drilling in a standing tree using a Resistograph tool (photo credit: Frank Rinn).

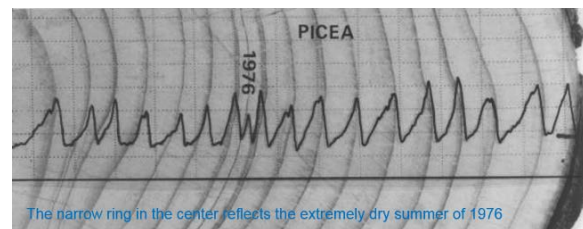


Figure 5. Resistance drilling profile obtained from a Norway spruce (*Picea abies*) revealing density variations inside tree rings (Rinn et al. 1996).

Precision of resistance drilling profiles

A significant amount of research has been conducted to explore the use of resistance drilling measurements for various applications such as tree ring analysis, tree decay detection, and structural timber condition assessment. Rinn et al. (1996) demonstrated that Resistograph charts of coniferous and deciduous wood revealed tree ring variations. Figure 5 shows an example of a drilling profile obtained from Norway spruce (*Picea abies*) revealing density variations inside tree rings caused by earlywood and latewood zones. The extremely dry summer of 1976 can be identified by the corresponding narrow ring in the center. In the ideal case of drilling in the radial direction (perpendicular to the growth rings), the tree ring parameters in dry wood revealed by Resistograph charts showed excellent matches with those revealed by the x-ray density charts, both qualitatively and quantitatively (Rinn et al. 1996). Chantre and Rozenberg (1997) compared Resistograph measurements with microdensitometry (MDM) on disks cut from 23-year-old Douglas-fir trees and found moderate to excellent correlations between profile

parameters (profile surface, profile energy, and mean density of the weighed profile) (r from 0.93 to 0.97). They concluded that the Resistograph appears to be better adapted to the evaluation of some whole-trunk parameters and is able to sum up in a single value one aspect of the standing tree global wood quality. Wang and Lin (2001) reported that the resistance drilling profile in *Taiwania* (*Taiwania cryptomerioides* Hayata) plantation wood revealed density variations inside tree rings caused by earlywood and latewood zones. The technique was also found useful in examining the effects of silvicultural treatments on density profiles and annual ring characteristics (Wang et al. 2003).

Wood density assessment

Research has quickly progressed to evaluate the potential of resistance drilling as an indirect method to measure density or specific gravity of dry wood. Some early studies demonstrated that there was a strong linear correlation between the mean drilling resistance and gross density of dry wood (Görlacher and Hättich 1990, Rinn et al. 1996). More recent studies on structural wood members also showed moderate to strong relationships between measured resistance values and wood density ($r^2 = 0.67$ reported by Ceraldi et al. 2001, $r^2 = 0.44$ reported by Zhang et al. 2009, $r^2 = 0.89$ reported by Park et al. 2006, $r^2 = 0.93$ reported by Bouffier et al. 2008, $r^2 = 0.62$ – 0.78 reported by Sharapov and Chernov 2014).

There has also been a growing interest in using the resistance drilling method for forest genetics field tests. In a tree genetic improvement program, Isik and Li (2003) evaluated the use of the Resistograph tool for rapid assessment of relative wood density of live loblolly pine trees in progeny trials. A total of 1,477 trees were sampled from 14 full-sib families of loblolly pine across the four test sites. They reported strong correlations among average drilling resistance values and wood density and strong genetic control at the family level. However, individual phenotypic correlations were found to be relatively weak. Similar results have also been reported by Gantz (2002), Charette et al. (2008), Gwaze and Stevenson (2008), and Eckard et al. (2010).

Friction factor

In a recent study, Oliveira et al. (2017) evaluated the use of resistance drilling for assessing wood specific gravity of young eucalyptus trees for pulpwood production. The genetic materials used consisted of fifty 34-month-old and fifty 62-month-old trees from *Eucalyptus grandis* Hill ex Maiden $\times$ *Eucalyptus urophylla* ST Blake clonal plantations. It was found that drill penetration depth had a significant effect on the relationship between average resistance amplitude and specific gravity. They observed a clear trend of weakening correlation as the drill penetration depth increased (Fig. 6), which could be attributed to the increased friction acting on the drill shaft. When a needle drill bit cuts through wood, wood chips remain in the drilling channel causing friction on the rotating needle shaft (Rinn 2012). The spade-type needle drill bit used in resistance drilling measurements typically has a 3-mm-wide triangular shape cutting head, which is twice the diameter of the needle shaft (1.5 mm). The drill bit is designed to decrease the shaft friction during resistance drilling measurements. The shaft friction was reported to be minimal in drilling wood of softwood species (Rinn et al. 1996) but was found to be significant in drilling wood of some tropical species such as eucalyptus (Nutto and Biechele 2015, Oliveira et al. 2017).

Concept of partial resistance drilling

Recent studies indicated that the use of the resistance drilling method can potentially be extended into tree genetic improvement and wood quality survey programs in which hundreds or even thousands of trees must be sampled for wood density information. One of the key issues with the resistance drilling method is related to the internal friction as the drill bit cuts deep into the tree. Because of the increased friction acting on the drill shaft, the accuracy of the relative resistance measurement can be affected. As a consequence, the predictive power of the amplitude parameter obtained from a resistance profile can be substantially decreased, especially in trees of larger diameter and greater wood density.

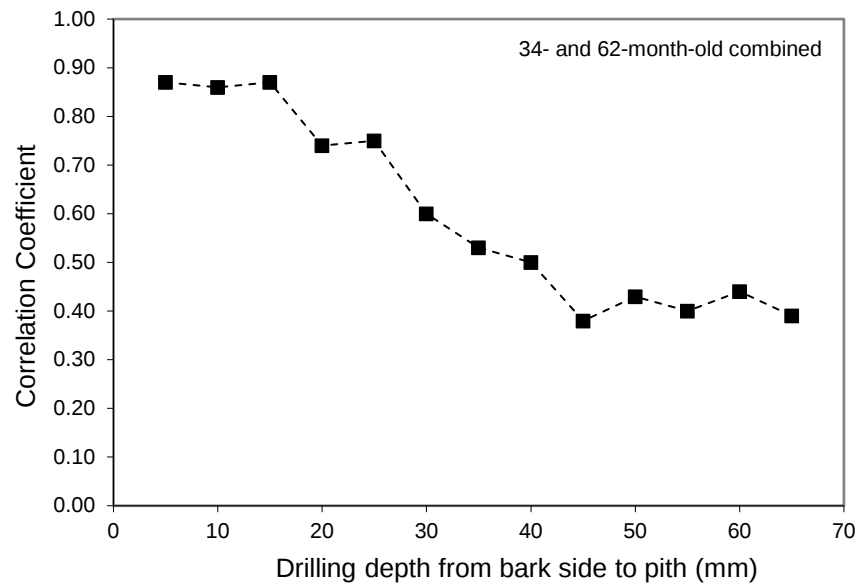


Figure 6. Correlation coefficient for the relationship between measured drilling resistance (expressed as amplitude in resistance profile) and specific gravity of 34- and 62-month-old *Eucalyptus grandis*×*Eucalyptus urophylla* trees as affected by the drilling depth (Oliveira et al. 2017).

A possible solution would be to conduct partial resistance drilling measurements on tree stems instead of drilling through the whole diameter, and assess the outer wood density of standing trees. If the outer wood density of a tree can be accurately determined through partial resistance drilling measurements, then the wood density models developed for the increment coring method can be used to predict the disk or whole-tree density using the outer wood density values. The validity of this partial resistance drilling approach needs to be tested in future research.

When selecting appropriate field nondestructive tools for determining wood density or specific gravity of standing trees, it is important that the solution must meet the needs of practicing foresters and reasonable estimates of average values with measurable errors will be more useful than expensive, highly technical procedures of greater accuracy. Although direct wood density measurements are often taken as the benchmark, wood density varies with stand age, site, silvicultural treatments, and genetics. A sound sampling strategy is critical in any wood density survey to ensure the validity of the method used. In general, the reasons for a nondestructive sampling procedure may include (1) assessing the wood quality of the forest resource available at a regional to a compartmental level; (2) examining the effects of site, climate, or silvicultural treatments on wood quality; and (3) assessing young trees for genetic improvement. For each of these reasons, different numbers of tree samples and sampling procedures will need to be carefully designed. A detailed discussion of nondestructive sampling methods can be found in Downes et al. (1997).

Conclusions

The basic increment core method has dominated research for more than half a century and has been used as a standard method for assessing wood quality of forest resources, determining biomass of ecosystems, and investigating climate history through dendrochronological analysis. Comprehensive wood density models have been developed for commercially important species that use outer wood cores and

knowledge of internal tree density distribution to fairly accurately predict the density of major tree components. With the development of SilviScan and near infrared spectroscopy instruments, more wood and fiber properties can be obtained from a single increment core sample, allowing comprehensive wood quality evaluation of plantation trees for genetic improvement, forest management, and optimal wood utilization. However, for many users or in many applications, increment core sampling and subsequent laboratory analysis are time-consuming and expensive. A more rapid field-type nondestructive method is needed in various research programs and forest operations.

The resistance drilling method has considerable advantages compared with the traditional increment coring method in terms of causing less damage to trees, faster data collection, and significantly less effort required for post data analysis. One factor that currently hinders the use of the resistance drilling tool for rapid wood density determination in trees is the internal friction encountered by the drill shaft as it cuts deeply into the tree stem. A partial resistance drilling approach coupled with knowledge of internal tree density distribution may offer an alternative to the widely used increment coring technique.

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Abstract

The 20th International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service Forest Products Laboratory in Madison, Wisconsin, USA, on September 12–15, 2017. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 20th Symposium is captured in these proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

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