Rapid Assessment of Wood Density of Standing Trees with Nondestructive Methods - A Review

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Abstract - Assessment of the quality of standing timber has become a crucial issue in the operational value chain as forestry and the wood processing industry are increasingly under economic pressure to maximize extracted value. A significant effort has been devoted toward developing robust nondestructive evaluation (NDE) technologies capable of predicting the intrinsic wood properties of individual trees, stems, and logs, and assessing the value of stands and forests. This paper provides a comprehensive review of the research results in the use of increment coring, needle penetration, nail withdrawal, and micro-drilling to determine wood density of standing trees.

Key Words - Resistograph, Pilodyn Wood Tester, Torsiometer, nail withdrawal, trees, wood density

I. INTRODUCTION

Density as one of the most important parameters of wood quality affects properties of various wood products. The traditional technique for determining wood density is volumetric method by extracting increment cores from trees and measuring the volume and mass of dry wood in laboratory. Although this method is generally accurate, it is both time consuming and labor intensive. Another technique capable of providing high accurate measurement of wood density is X-ray densitometry. The advantages of this technique are its ability to clearly obtain wood density values at different density zones and allowance of densitometric comparisons between radii of the same tree, between trees on the same site and mean density values between sites. However, X-ray method is relatively high cost and also time consuming as increment core method. Therefore, either increment core technique or X-ray method does not satisfy the requirements for a rapid and economical evaluation of wood density in standing trees.

For the purpose of achieving a much more rapid, reliable, and economical wood density measurement in standing trees,
several nondestructive methods and instruments have been evaluated by some researchers, which include Torsiometer, Pilodyn Wood Tester, nail withdrawal, and micro-resistance drilling (Resistograph®).

II. NDT TOOLS EVALUATED

A. Torsiometer

Torsiometer technique is one of the methods investigated for rapid assessment of wood density on trees (Nicholls and Roget 1977, Cown 1978). The force required to turn an increment borer at a known depth in a tree trunk is recorded with the aid of a hand-held tool called Torsiometer (Figure 1). In practice, a bark window is cut and the boring operation is initiated using a starting handle. Typically a 5 mm borer is used and the penetrating depth is 38 mm in field application.

B. Pilodyn Wood Tester

Pilodyn Wood Tester is a handheld instrument that injects a spring-loaded needle into the wood and reads the depth of needle penetration in mm (Figure 2). It was initially developed in Switzerland to collect quantitative data for evaluating wooden poles. Use of Pilodyn in standing trees requires removal of a bark patch, followed by driving the needle into the wood under a known force. There are different types of Pilodyn Wood tester because of the differences in needle diameter.

C. Nail Withdrawal

This method is proposed based on the relationship between wood density and the maximum force required to withdraw a nail driven into the tree (Nicholls 1985). Hydraulic pressure is used to extract the nail and the maximum value is used as a measure of the maximum withdrawal force. The equipment comprises the pump and gauge, the hydraulic cylinder and the nail holder (Figure 3). The hand-operated pump is coupled to the pressure gauge which is fitted with the resettable maximum-value indicator. A pressure hose leads to the hydraulic cylinder, the cutaway portion of which reveals the coupling piece. The nail holder, spare nail and medal thread screw are included.

D. Resistance Micro-Drilling (Resistograph®)

Resistance micro-drilling tool, also called Resistograph®, is a mechanical drill system that measures the relative resistance (drilling torque) as a rotation drill bit is driven into the wood at a constant speed (Figure 4). It produces a chart showing the relative resistance profile for each drill path. Drill resistance RD (in Nm s/rad) is defined as

\[ R_D = \frac{T}{\omega} \]

Where T is drilling torque (Nm) and \( \omega \) is angular speed (rad/s).

A resistance micro-drilling tool typically consists of a power drill unit, a small-diameter drill bit, a paper chart recorder, and an electronic device that can be connected to the serial interface input of any standard personal computer. The
diameter of the drill bit is typically 2 to 5 mm, so any weakening effect of the drill hole on the wood material is negligible.

Figure 4. Resistograph® system (Rinn et al. 1996)

III RESEARCH RESULTS

A. Torsiometer
Nicholls and Roget (1977) carried out tests on Pinus radiate showing correlations between basic density and Torsiometer readings of r=0.94. Trials in New Zealand on P. Radiate yielded correlations ranging from r=0.74 to 0.94 (Cown 1978). These results provided a good prediction of wood density of living trees. This instrument still has to use an increment borer in the field even though it greatly reduces the laboratory workload. A reading can be taken reasonably quick on a tree, however operator fatigue may affect results. Splitting can occur at the site of the boring, and this may produce variability of measurement.

B. Pilodyn Wood Tester
A series of studies were conducted to evaluate the Pilodyn wood Tester for nondestructive assessment of wood density. The relationship between penetration depth and wood density was examined using a Pilodyn with a 2.5-mm diameter needle. Cown (1978) compared the results from Pilodyn with those from the Torsiometer method as regards accuracy for predicting the wood density measured from increment cores. He found the Pilodyn results were obtained more rapidly and were more closely related to the mean tree outer-wood density (r=0.86 as compared to 0.79 for the Torsiometer, Figure 5). A correlation coefficient of -0.71 was obtained for the data relating penetration depth to the density of increment cores (Hoffmeyer, 1978). The relationship was also examined between Pilodyn penetration and specific gravity of trees. A significant linear relation with the correlation coefficient r of -0.81 was revealed between penetration and specific gravity of southern pines (Taylor, 1981).

Three types of Pilodyne Wood Testers, 6J-2.0 mm diameter needle, 18J-3.0 mm diameter needle and 18J-2.5 mm diameter needle, were evaluated for their efficiency as an indirect selection technique to improve mature wood specific gravity in trees (Sprague et al., 1983). In this investigation, they found that wood properties influencing Pilodyn needle penetration were heritable (h²=0.06 to 0.46) and had a strong genetic correlation (r) to wood specific gravity for two of the three instruments tested, namely 6J 2.0 mm diameter needle and 18J-3.0mm diameter needle, of 0.89 and -0.82 respectively. Indirect selection using 18J Pilodyn with a 3.0mm diameter was estimated to be 83.6 percent as efficient in improving wood specific gravity as directed selection for the trait itself.

Gough and Barnes (1984) evaluated Pilodyn technique for determining wood density of 15 Pinus elliottii Engelm. families in the progeny tree test. This study suggested using the Pilodyn method to rank family for wood density in large provenance trials and progeny tests. Significant correlations between species and provenance means (r=0.66 to 0.90) were found for all comparisons of three methods of gravimetric, electronic densitometer and Pilodyn (6J-2.5mm) wood tester for assessment of wood density at both sites in Brazil (Moura et al., 1987). They concluded that the pilodyn was as efficient as the densitometer for ranking the material at species and provenance mean level but it was not reliable enough to screen for density at individual tree level.

Greaves et al. (1996) found that the high repeatability of Pilodyn penetration suggests that only two observations per tree would be required for indirect selection of density. A series of comparisons were made between Pilodyn penetration and wood properties (Wu et al., 2010). They found that there were significant differences between Pilodyn penetration of different treatments, different directions and different clones. The correlations between Pilodyn and wood properties were generally strongly negative with a range of coefficients (r) from -0.43 to -0.75. The results indicated that wood basic density and MOE can be predicted by using Pilodyn.

C. Nail Withdrawal
Nicholls (1985) reported a method for determining wood density in standing trees based on the relationship between wood density and the maximum force required to withdraw a nail driven into the tree. He carried out the tests on 600 trees using the equipment which was described using hydraulic means to extract the nail and maximum hydraulic pressure as a measure of the maximum withdrawal force. He found a cylindrical nail was suitable for the low-density trees such as pines (r=0.91 between pressure and density), whereas a nail of elliptical cross-section yielded the best results for testing
denser wood (r=0.92). Compared with Pilodyn and Torsiometer methods with respect to precision, test time and damage to the tree, hydraulic means can be satisfactorily used to assess wood density in standing trees for a range of species covering a wide spectrum of density.

![Figure 5. Comparison of Pilodyn Torsiometer assessments of Clonal Trial 944/4 (Cown. 1978)](image)

A comparison was made on tree-ring density values obtained by radial resistance boring and by X-ray densitometry on dry timber of several different species (Rinn et al., 1996). The results indicated that the mean levels of the relative resistance from the Resistograph profiles closely correlated to the gross density of the dry wood (R² >0.8). The resistance profile even revealed density variations within and between the tree rings and density variations caused by decay.

Chantre and Rozenberg (1997) conducted experiments to record Resistograph (RST) and Micro-densitometry (MDM) on same trees compared the two types of profiles. The results showed moderate to excellent correlations between profile parameters, especially for the surface of the profile, profile energy and mean density of the weighed profile (r from 0.93 to 0.97). Earlywood density, minimum ring density and latewood width are not well estimated. They concluded that Resistograph seems better adapted for the evaluation of some whole trunk parameters, able to sum up in a single value one aspect of the standing tree global wood quality.

Isik and Li (2003) evaluated the use of Resistograph tool for rapid assessment of relative wood density of live trees in progeny trials. A total of 1477 trees were sampled from fourteen full-sib families of loblolly pine across the four test sites (Figure 6). For each family, wood density was measured with the traditional volumetric method and then compared with the Resistograph readings (amplitude). This study showed that Resistograph amplitude had weak (0.29) to moderate (0.65) phenotypic correlations with wood density on an individual-tree basis over the four sites. They suggested that the Resistograph seems to have advantages over other tools used to measure relative wood density of live trees.

![Figure 7. Correlation of specific gravity and average resistance (Park et al. 2006)](image)

Park et al. (2006) conducted Resistograph measurements on larch and Korean red pine specimens manufactured from deteriorated wooden members of ancient building to obtain the correlation between the specific gravity and drilling resistance (Figure 7). They found the variations of the wood member with termite or fungi and the crack could be detected exactly but the knot couldn’t because the drill could pass by or could not penetrate the knot.
and two hardwood species (Gantz, 2002). Resistograph data was also used to estimate genetic parameters of wood density of these species and compare them to x-ray densitometry. These results indicated that it is possible to use the Resistograph in genetic tests for the indirect selection of trees with desirable wood density. Gwaze and Stevenson (2008) investigated the relationship between wood density and drill resistance measured by a Resistograph. At the individual-tree level the linear relationship between wood density and drill resistance (amplitude) was weak and positive ($R^2 = 0.23$) but was stronger ($R^2 = 0.47$) at the family mean level (Figure 8). Genetic relationship between the two traits was moderately strong ($r_s = 0.74$). Individual-tree heritability estimates for both traits were high ($h^2 = 0.47$ for wood density and $h^2 = 0.64$ for amplitude). The efficiency of using the Resistograph to indirectly select for improvement of wood density was 86% at individual-tree level. They found the linear relationships at individual-tree level to be weak ($R^2 = 0.21-0.44$). However, at family mean level, the relationship between amplitude and wood density was stronger in their study ($R^2 = 0.85$) than in ours ($R^2 = 0.47$).

Kahl et al. (2009) estimated the density of dead logs of Norway spruce in four different decay stages by Resistograph measurements and made comparison with conventional predictors of wood density such as fast quantitative field estimates. They found the predicting model of wood density only containing drill resistance as a predictor explained 65% of the variation in wood density. Also, the relationship between drill resistance and gravimetric wood density was sensitive to the decay status (Figure 9).

IV. COMPARISON OF NDT TOOLS FOR FIELD APPLICATION

Pilodyn has some advantages over both the traditional increment cores method and Torsiometer method. First, Pilodyn is outstanding in tree improvement trials in the respect of amount of density assessment for its efficiency and productiviy, particularly in young stems where bark removal is easy and rapid. However, in older trees, Pilodyn is restively time-consuming on the thick bark removal. Second, though Torsiometer operation is recommended since its more efficient in this practice, the use of the Torsiometer requires insertion and removal of an increment borer, which is not only much more time-consuming but introduced an extra source of error, namely the condition of the cutting edge (Cown 1978).

Damage to standing trees caused by the Pilodyn is much less than that resulting from Torsiometer operation. Pilodyn leaves a hile 2.5mm in diameter and up to 20mm deep when working, but an increment borer used for extracting 5mm diameter cores leaves a channel about 11mm in diameter and at least 40mm deep when Torsiometer works. The Torsiometer reduces the overall work load by limiting the laboratory time as compared to increment core methods, but the field effort is essentially similar. The Pilodyn can reduce field time considerably, as operation of the instrument is much more rapid. A disadvantage of both the Pilodyn and Torsiometer instruments is the relative insensitivity of the scales and the consequent potential error in interpreting between narrow limits. In practice it is unrealistic to record Pilodyn results at better than 0.5 mm intervals, despite the fact that 1 mm represents about 20kg/m3 (Cown 1978).

Compared with the Pilodyn, Resistograph values do not vary from one operator to another. The needle is driven into the tree constantly with a fixed drill speed. The drilling does not require the bark to be removed, so it is less damaged than
Pilodyn on young trees. Resistograph method measures whole cross-section of a tree stem from bark to bark, but Pilodyn needle can penetrate only the first few outer rings. Resistograph applied on the tree leaves a 1.5mm diameter hole that is almost invisible.

Compared with the other methods, Resistograph is portable and easy to handle both in the field and in the lab, and the data collection and analysis is cheaper and more rapid. The resolution of the Resistograph profile is generally a little lower than X-ray (0.04 and 0.06). And the scale depth is different. With the further development of drilling and analytical techniques, Resistograph is expected possibly to be used to study within-tree variation in relative density, juvenile-mature wood transition zones, as well as earlywood and latewood traits. However, one of the potential drawbacks of the Resistograph is that the moisture content of live trees affects the estimates of density (Isik and Li 2003).

From the literature, it has been concluded that the Resistograph is of great valuable for rapidly assessment of the relative wood density of standing trees. The Resistograph system is easy to use in the field, relatively nondestructive, and rapid. The profiles produced by drilling allow estimation of diameter inside bark and, with further refinement, might provide information on within-tree variation in wood density.

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