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A Non-Destructive Field Method for Measuring Wood Density of Decaying Logs

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Decaying dead wood density measurements are a useful indicator for multiple purposes, such as for estimating the amount of carbon in dead wood and making predictions of potential diversity of dead wood inhabiting fungi and insects. Currently, qualitative decay phases are used as wood density estimates in many applications, since measuring the density is laborious. A quantitative measure of density would, however, be preferred over the qualitative one. Penetrometers, which are commonly used for measuring the density of standing trees, might also be applicable to dead wood density measurements. We tested the device for making quick, quantitative measurements of decaying logs. The penetrometer measures the depth into which a pre-loaded spring forces a pin in the wood. We tested pins of 5 and 10 mm diameter together with an original 2.5 mm pin and compared the results with gravimetric density measurements of the sample logs. Our results suggest that the standard pin works for less decayed wood, but for more decomposed wood, the thicker 5 mm pin gave more reliable estimates when the penetration measures were converted to densities with a linear regression function (R^2=0.62, F=82.9, p=0.000). The range of wood densities successfully measured with the 5 mm pin was from 180 to 510 kg m^{-3}. With the 10 mm pin, the measuring resolution of denser wood was compromised, while the improvement at the other end of density scale was not large. As a conclusion, the penetrometer seems to be a promising tool for quick density testing of decaying logs in field, but it needs to be modified to use a thicker measuring pin than the standard 2.5 mm pin.

Keywords carbon stock, coarse woody debris, decaying wood, wood decomposition, penetrometer, pilodyn
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1 Introduction

The amount of dead wood is one of the target variables in the modern forest inventories, since quantity and quality of dead wood have direct implications for forest biodiversity and forest carbon stock. The community structure of wood inhabiting species change and number of active species increases with decreasing density (mass loss) of decomposing wood (Rajala et al. 2010, Rajala et al. 2011). Thus, the density of decaying wood is an important variable when the habitat availability for the wood inhabiting species is evaluated. In carbon inventories, the target variable is the mass and carbon amount of dead wood, which also requires quantification of wood density (IPCC 2003). However, direct wood density measurements are not available due to the lack of appropriate techniques and instruments.

In practice, the quality of decaying wood (or coarse woody debris,) is most often recorded only as rough decay classes. They are relatively easy to determine on the basis of visual features of dead trees (e.g. Kruys et al. 2002, Aakala 2010) or by a simple knife penetration test in field conditions (Mäkinen et al. 2006, Hottola and Siitonen 2008). However, in forest carbon inventories and in many other applications, the density of decaying wood is a variable required in the analyses. Thus, mean density estimates obtained from literature are used in calculations, which introduces large uncertainties to e.g. forest carbon stock estimates. In general, decay classes developed by different authors are not consistent. Moreover, numerous studies have shown that density variation within each decay class is wide, with the range of wood density within a class varying from one site to another and the density distribution of classes greatly overlapping (e.g. Næsset 1999, Mäkinen et al. 2006, Rajala et al. 2010). While decay classification is a very effective way to describe variation in the dead wood quality and it is successfully used in many studies, a more accurate non-subjective method with a continuous scale is required e.g. for quantitative analysis of forest carbon stock.

Accurate wood density measurements based on the volume and dry weight of a sample require measurements in a laboratory and destructive sampling, which is not applicable to, for instance, monitoring purposes. For measuring the density variation in field conditions, one potentially applicable method uses a spring-loaded penetrometer called Pilodyn (e.g. Micko et al. 1982), which is an instrument originally developed for determining the degree of soft rot in wooden telephone poles (Hansen 2000). The Pilodyn wood tester, which measures wood strength by driving a blunt steel pin into the tree with a force developed by a spring, is successfully applied in ranking provenances for wood quality (Sprague et al. 1983, Greaves et al. 1996, Lee and Connolly 2010). The depth of pin penetration is indicated on the instrument, and the readings are correlated with wood density. The Pilodyn itself does not provide density estimates, but the instrument has been calibrated to density measurements of living trees in numerous studies (e.g. Micko et al. 1982, Sprague et al. 1983). This rapid wood testing instrument might be a valuable tool also in density measurements of dead trees, but its applicability to highly variable wood densities of decaying wood has not been tested until now.

The aim of this study was to test the applicability of the Pilodyn penetrometer to quantitative density measurements of decaying wood, and to further develop a technique that can be applied in non-destructive wood density testing in field conditions, as well as to calibrate the developed method for decaying logs of Norway spruce (*Picea abies* (L.) H. Karst.).

2 Material and Methods

2.1 Study Sites and Sampling Design

We studied the density of decaying wood at two unmanaged Norway spruce dominated sites in Southern Finland (Petäjäjärvi site 61°54'N, 23°34'E, altitude 165 m ASL; Sipoo site 60°27'N, 25°11'E, altitude 65 m ASL). The sites are located in southern boreal vegetation zone, with effective mean temperature sums of 1130 and 1290 degree-days (with threshold of 5ºC) in Petäjäjärvi and Sipoo, respectively. Both sites represent a typical intermediate fertility class of Norway spruce dominated sites (mesic heath forests (MT) accord-

Table 1. Statistics of the weight and volume based density measurements. The numbers of observations (n) refer to the total number of measured logs (All) and to the number of valid Pilodyn readings made with the 5 mm and 2.5 mm pins at the Petäjäjärvi study site as well as with the 10 mm pin at the Sipoo site.

	Petäjäjärvi			Sipoo	
	All	5 mm	2.5 mm	All	10 mm
n	101	53	37	98	77
Average (kg/m^3)	275	353	383	291	303
StDev (kg/m^3)	105	73	48	97	86
Min (kg/m^3)	122	180	295	74	85
Max (kg/m^3)	513	513	513	508	508

ing to Cajander's classification (Hotanen et al. 2008)). Within the established study plots of 5625 m^2 (75 m x 75 m), all fallen dead trees with diameter over 5 cm (measured at the height of 1.3 m from the tree base) were carefully located, measured for dimensions and decay class, and their tree species were recorded. For density measurements, we sampled approximately 100 fallen logs per site (Table 1). Sampling was stratified according to decay classes to obtain sufficient number of observations from less frequent decay phases. In practice, from Petäjäjärvi site we took every fifth and every second log of decay classes 1 and 4, respectively. All logs of decay classes 2, 3, and 5 were sampled. In Sipoo, we applied a similar approach.

2.2 Density Measurements from Wood Discs

Wood sample discs of approximately 5 cm in width were cut with a chain saw from the mid part of the sample logs. The diameter range of the sample discs was from 5 cm to 42 cm. Discs were sealed in plastic to avoid desiccation and stored at –18ºC until density analysis. The wood density of each disc was measured with the water displacement method (Olesen 1971). The volume of the frozen sample disc was recorded as the mass of displaced water. The disks were then dried and dry weight measured. The density was calculated as the ratio of dry weight to fresh volume.

2.3 Wood Decay Phase Testing with the Knife Method

Prior to wood sampling, the decay class of a log was determined from the sampling point according to the classification that is based on visual observations and testing with a knife, i.e. pressing a knife into the log and classifying the density according to the penetration depth and force required (Mäkinen et al. 2006, Hottola and Siitonen 2008). Accordingly, five decay classes were distinguished: (I) still hard wood – knife blade penetrates a few millimetres into the wood; (II) still fairly hard wood – knife blade penetrates 1–2 cm into the wood; (III) outer layer of the log fairly soft, core still hard – knife blade penetrates 3–5 cm into the wood; (IV) soft throughout – knife blade penetrates all the way into the wood; (V) very soft – wood structure of logs already collapsed. Thus, in the case of decay classes 1–3, the decay class determination is based on the properties of the surface layer of the tested log.

2.4 Wood Testing with a Pilodyn 6J Penetrometer and Modified Pins

Prior to sawing of the sample discs, wood density was tested with a commercially available penetrometer, Pilodyn 6J (manufactured by Proceq, Zurich, Swizerland) (Fig. 1). Pilodyn is designed for estimating the structural strength of wood; it contains a spring that is pre-loaded to a constant tension. When triggered, the spring drives a blunt steel pin, initially touching the log surface, into the wood. The device has a scale (from 0 to 40 mm) for measuring the depth the pin penetrates

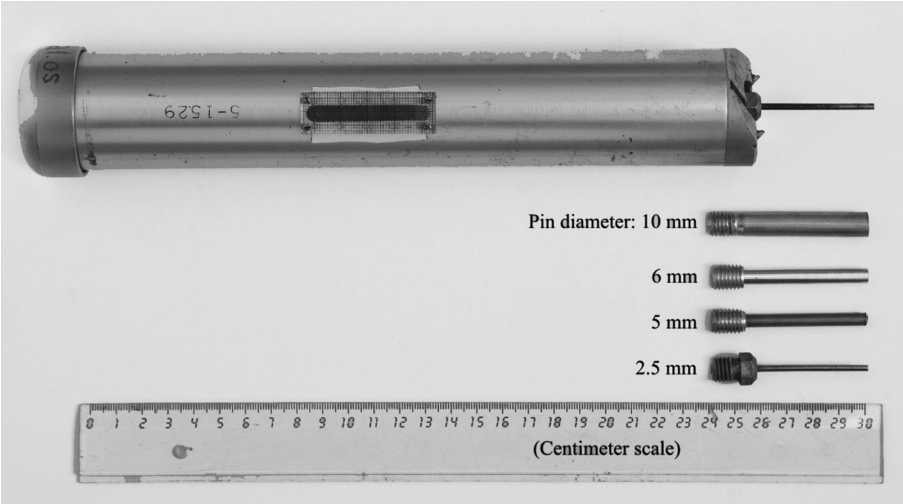

Fig. 1. The Pilodyn J6 instrument with the standard 2.5mm pin attached. The measuring scale is shown in the middle of the device. The 5 mm pin is from brass tube and steel pin core, 6 mm pin is made of a model airplane landing gear axle, and the 10 mm pin is made of an ordinary steel bolt. All pins attach with a M10 thread to the instrument.

into the wood. Since the maximum depth of penetration is 40 mm, the readings reflect wood properties of the surface layer. The standard 2.0 or 2.5 mm pin is intended to be used for measuring standing trees or the strength of wooden telephone poles. Since our preliminary tests had shown that with the standard pin the penetration readings of decayed logs were often beyond the measuring scale of the meter, we modified the instrument by building two additional, cylindered and blunt test pins that were of the same length as the original ones, except for larger diameters of 5 and 10 mm (Fig 1).

The 10 mm test pin (Fig. 1. to the right) was made simply from a M10 machine bolt with an unthreaded shaft at the root by sawing the bolt so that 12 mm of the thread remained and the pin stem came from the unthreaded shaft of the bolt. The Pilodyn device uses M10 threads to attach the penetration pin so as to avoid the need for further attachment devices. Another pin with a 5 mm diameter was build from a short M10 bolt, to which a 5 mm outer diameter brass tube with a 3 mm steel wire core was attached. After some use, the outer edge of this brass tube started to deform, indicating that brass is too soft material for the pin. After the testing phase, we found a perfect source for a smaller, solid-steel measuring pin: a steel axle shaft for a model airplane landing gear, manufactured by Kavan (www.kavan.de; part no. 6165). This has an unthreaded shaft of 6 mm in diameter and an M10 thread in one end; by sawing the shaft to a proper length we got a solid measuring pin with an M10 thread in one end and a 6 mm shaft in the other. In the future, we will use that as the measuring pin.

2.5 Data Analysis

Altogether 101 wood logs were measured at the Petäjäjärvi site. We made three Pilodyn readings per log with both the 2.5 and 5 mm pins. The three measurements were made on the same circumference of the log, on both sides and on the upper surface. For the analysis, the average of those three readings was used. Logs where at least one of the measurements was beyond the Pilodyn measurement range (i.e. the pin was pushed more than 40 mm into the wood with the spring stopping) were discarded from the data. This left us with 53 valid measurements with the 5 mm pin and 37 measurements with the 2.5 mm pin. At the Sipoo site, only the 10 mm pin was used with a

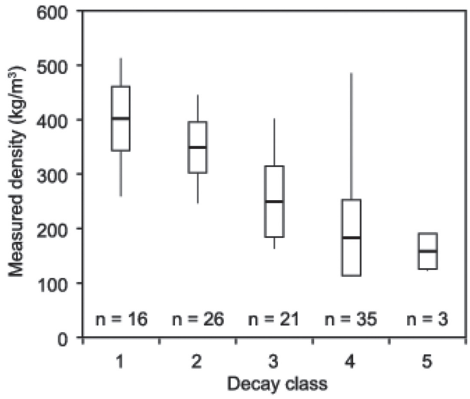

Fig. 2. Distributions of decaying wood densities according to decay classes, and the number of sampled logs (n) in each density class at the Petäjäjärvi site. The white bars show the standard deviation of densities within a class, with average indicated by the horizontal line. The lines show the overall maximum and minimum within each decay class.

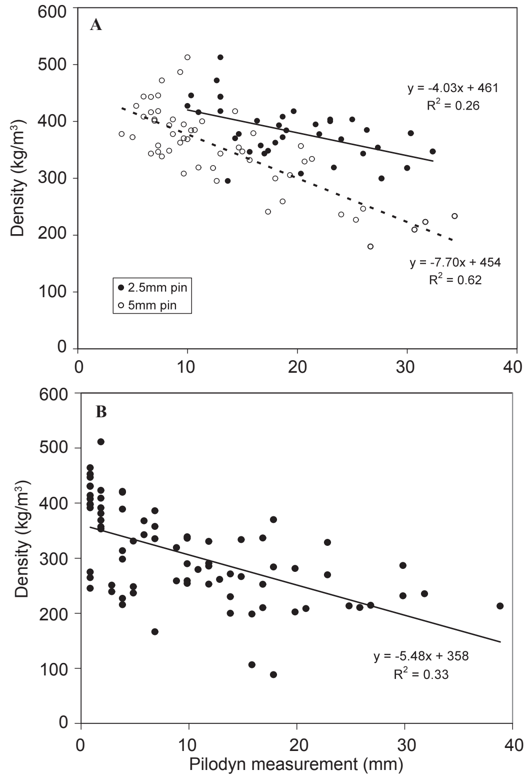

Fig. 3. Relationship between wood density and Pilodyn measurements from Petäjäjärvi, with the 2.5 mm and 5 mm pins (Fig 3A), and from Sipoo, with the 10 mm pin (Fig 3B). The solid and the dotted lines show linear regression models, with the equations and R^2 values, fitted to the data.

single measurement per log. With the same criterion for discarding unsuccessful measurements, we ended up with 77 valid measurements out of the 99 sample logs.

We used a simple linear regression model to couple the Pilodyn readings with the laboratory density measurements. We also tested some more complicated models, such as polynomial and exponential ones, to see if using these would improve the model prediction ability. The models were fitted independently to all three data sets.

3 Results

The average wood densities of sampled decaying logs were 275 kg m^{-3} and 291 kg m^{-3} at the Petäjäjärvi and Sipoo sites, respectively, with similar standard deviations and almost identical ranges of densities (Table 1). The wood density of sampled discs varied from 73 to 513 kg m^{-3}. When we classified the samples by the qualitative decay classes (1–5), the mean densities within classes indicated a consistent trend from one decay class to another. However, the density variation within a class was large and distributions of densities between classes were considerably overlapping (Fig. 2).

Before further analysis of the Pilodyn penetrometer readings, we had to discard the outliers, i.e. measurements where the reading was beyond the measuring scale; in practice, this means that the measured log was too soft to stop the pin before it moved outside the scale of the meter. The original 2.5 mm pin turned out to be too thin for measuring decaying wood, as 63% of the measurements were beyond the scale. The 10 mm needle had less readings beyond the meter scale, but had an inadequate resolution at the dense end of the scale, giving almost similar readings to a range of wood densities (Table 2, Fig. 3B). The 5 mm pin seemed to give the best range and resolution of measurements at our sample sites.

Table 2. Statistics of the Pilodyn readings with the different pin sizes. A single measurement at the Petäjäjärvi site was the average of three measurements, while the Sipoo data consists of single measurements.

	Petäjäjärvi 5 mm	Petäjäjärvi 2.5 mm	Sipoo 10 mm
n	53	37	77
Average (mm)	13.2	19.4	10.2
StDev (mm)	7.5	6.0	9.0
Min (mm)	4.0	10.0	1.0
Max (mm)	34.3	32.3	39.0

We fitted a linear regression model to predict gravimetric wood density using the Pilodyn readings (Fig 3A). The 5 mm needle gave the highest value of explained variation (R^2), 0.62 (F=82.9, p=0.000), while the values for the 2.5 and 10 mm pins were 0.26 and 0.33, respectively (Fig 3A and 3B). This supported our conclusion that the 5 mm pin was best suited for measuring the density of decaying wood. Even with the 5 mm pin, the variation of wood density was still slightly underestimated with the linear model due to the limitations of the Pilodyn device, i.e. reduced resolution for the denser logs and lack of pin range for the less dense ones (Fig 4). With the 5 mm measuring pin, the lower detection limit of wood density seemed to lie approximately at 180 kg m^{-3}, and densities lower than that were not successfully tested with either standard or modified version of the device (Table 2).

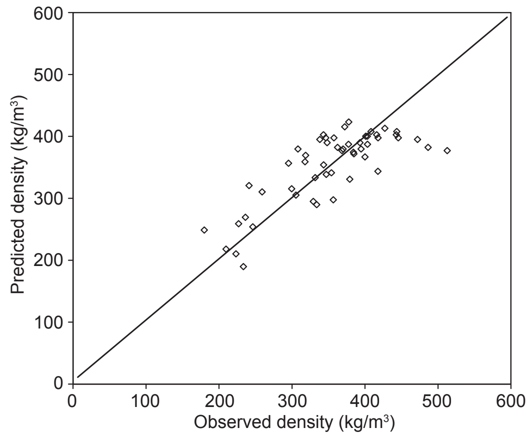

Fig. 4. Observed vs. predicted decaying wood densities from the measurements with the 5 mm pin.

4 Discussion

The range of wood densities that can be successfully measured with a quick field test based on the modified 5 mm pin Pilodyn device varied from 180 to 510 kg m^{-3}. This range represents the densities during early and mid-decay phases, i.e. decay classes 1–3 of the classification commonly applied in field surveys (Mäkinen et al. 2006, Hottola and Siitonen 2008). It was not possible to measure the most decayed logs with wood density lower than 180 kg m^{-3} using the presented penetrometer technique. The minimum wood density covered by the original instrument (with the 2.5 mm pin and inception energy of 6 joules) applied to living trees was reported to be 300 kg m^{-3} (Micko et al. 1982). The extended wood density range covered by our modified version of the Pilodyn wood tester enables measurements that are useful for studies on the diversity of wood decaying fungi, such as a large proportion of polypore species that thrive on logs in the mid-phases of decaying process (decay classes 2–4) (Renvall 1995, Rajala et al. 2010). In addition, the penetrometer measurements provide wood density readings required by more detailed habitat models of decomposers.

Even though the measurements with the Pilodyn penetrometer using the 5 mm pin showed a quite good coverage of the density variation, the overall range still underestimated the total variation of the first-hand density measurements. This is probably due to the limitation of the instrument at either end of the measuring scale. At the denser end of the logs, the resolution of the readings on a simple millimetre scale may not be sufficient to present the actual density variation. On the other hand, at the other end reaching the physical end limit of the pin and spring travel compromised the data. This effect was especially pronounced as we decided to discard each measurement where at least one of the three repetitions was beyond the meter limits. Due to the considerable spatial variation of wood density, the number of discarded samples was quite large. We tested the method with a 5 mm pin that was manufactured for testing purposes and had problems with the durability of the material. A commercially available 6 mm pin was not tested, but we believe that, after calibration, it should work in a similar manner as the 5 mm pin. The 6 mm pin is made of solid steel and as such should show less wear in repeated use.

Detection limit has also been a major problem in the other non-destructive wood testing methods developed for density measurements of decaying wood. In addition to standard density measurements, Creed et al. (2004) used a penetrometer designed for soil samples and a resistograph used for living trees. Despite the observed relationship between the alternative techniques and the direct density measurements, their techniques could not explain more than 32% of the wood density variation. The penetrometer applied in their study gave readings of maximum value for a wide range of wood densities, and the resistograph gave zero readings for several samples of both of the studied tree species. Together with a spring penetrometer quite similar to the one tested in this paper, Larjavaara and Muller-Landau (2010) also tested a dynamic penetrometer, which utilizes a moving weight to apply a standardized amount of kinetic energy to insert the pin into the wood sample. Their instruments were designed for dead wood and performed better than those tested by Creed et al. (2004), but still a considerable amount of density variation remained unexplained. Kahl et al. (2009) presented a method that was able to explain 65% of the density variation of dead Norway spruce logs on the basis of measurements of drill resistance in wood with a resistometer, which can be used in the field. However, each measurement usually takes 2–3 min and the obtained data requires further processing to yield density estimates. Furthermore, the number of consecutive measurements is limited to 30–80 by battery capacity. An advantage of the method is that a drilling needle with the length of 45 cm can measure the drilling resistance across a tree and average density can be derived taking density variation within a sample disc into account. Since the length of the pin in the spring penetrometer tested in our study was 4 cm, readings reflected wood properties of the outer part of the log and potential spatial variation in wood density was ignored. In smaller logs this is of minor importance, because inner part represents only a small portion of the volume, but with large trunks that are potentially decayed by heartwood rot, bias might be remarkable when density is estimated by testing only the outer part by knife or by penetrometer.

Our measurements with the penetrometer managed to account for 62% of the observed wood density variation. The modified Pilodyn instrument tested in this study is the first attempt to utilise a quick non-destructive wood density testing instrument that may be calibrated to density measurements on decaying wood. To improve the measuring range, the Pilodyn device would need to be modified to allow a longer travel of the measuring pin. To further develop the method, measurements and calibration for logs from different tree species are required.

5 Conclusions

The advantages of the tested and modified penetrometer are that it is very quick to use (one measurement takes only a few seconds) and non-subjective. Commonly used determination of decay classes necessitates training of the surveyors to achieve consistency, and it is dependent on the subjective decision of the surveyor even after good instructions and careful training. Even though the penetrometer readings are read from discrete measurement points (compared to the laboratory measurement that uses samples with larger volumes of wood) and therefore more vulnerable to the considerable spatial variation in the density of decaying wood, the sample size can easily be increased even to get an estimate of the variability of density. In addition, it provides density estimates on a continuous scale, which enables the use of more effective means of data analyses than the use of qualitative decay classes.

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