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Progressive, idiosyncratic changes in wood hardness during decay: Implications for dead wood inventory and cycling

Brad Oberle [a,b,*], Kevin Dunham [c], Amy M. Milo [a], Maranda Walton [c], Darcy F. Young [a], Amy E. Zanne [a,b]

[a] Department of Biological Sciences, George Washington University, 2023 G St. NW, Washington, DC 20052, USA
[b] Center for Conservation and Sustainable Development, Missouri Botanical Garden, St. Louis, MO 63166, USA
[c] Department of Biology, University of Missouri-St. Louis, St. Louis, MO 63166, USA

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A B S T R A C T

Coarse woody debris (CWD) plays important roles in forests including carbon storage. Calculating the size of this carbon pool from survey data entails estimating the volume and density of dead wood. Density is highly correlated with other mechanical parameters in intact wood, explaining how penetrometers, which measure a mechanical parameter related to hardness, have proven useful for estimating dead wood density. However, the relationship between wood density and hardness varies with three key factors that vary in CWD: moisture content, tree species and degree of decay. We estimated how these factors influence penetrometer measurements across conditions ranging from lab standards to field conditions during a CWD survey. When measuring experimentally decayed wood under standard conditions, penetrometer distance was highly correlated with sample density and the effects of moisture content and interspecific variation were similar to those expected from analyses of intact wood. However, when we relaxed experimental controls and included samples that had decayed for different lengths of time, these relationships shifted such that penetrometer measurements no longer correlated with intact wood hardness and tended to increase relative to density and moisture content. The decoupling of mechanical properties in decaying wood is consistent with case hardening, which developed differently in different species and contributed to high variability in penetrometer measurements during the CWD survey. These results demonstrate temporal changes in decaying wood mechanical properties that have implications for surveying CWD and understanding carbon dynamics in temperate hardwood forests.

1. Introduction

Dead wood plays important roles in forest ecosystems. It provides habitat for wildlife and microbes, fuel for fire and contributes to nutrient cycles (Brown, 2002). In the forest carbon cycle, large pieces of dead wood, or coarse woody debris (CWD[1]), can represent a substantial pool that accounts for up to 45% of aboveground biomass and 20% of all carbon (Wilson et al., 2013). However, the absolute and relative size of the CWD pool varies in space and time (Woodall and Liknes, 2008) with important consequences for estimating forest carbon flux with global change (Woodall, 2010). Shifting climate has contributed to forest dieback events and huge influxes of carbon to the CWD pool (Adams et al., 2009). Whether this carbon feeds back into the climate system depends on how quickly it is released during the dynamics of CWD decay (Moore et al., 2013).

Because of the importance of dead wood, many forest inventories implement CWD surveys. Surveys that quantify dead wood biomass and its consequences for carbon cycling must estimate dead wood volume and density. Both values are difficult to measure accurately and efficiently in extensive surveys. One of the fastest and most widely used methods for estimating dead wood density is based on decay classification (Harmon et al., 1986). In this approach, surveyors assign pieces of CWD to ordered decay classes representing the degree of decay relative to intact wood by assessing the presence and extent of key indicators, such as bark retention or shape deformation (Pyle and Brown, 1998). A recent evaluation of a decay classification system in a Canadian forest found a high correlation with dead wood density (Seedre et al., 2012). Using these relationships, inventory managers have estimated forest and decay class-specific biomass and C conversions (Harmon et al., 2013).

* Corresponding author at: Department of Biological Sciences, George Washington University, 2023 G St. NW, Washington, DC 20052, USA. Tel.: +1 314 640 0001.
E-mail address: brad.oberle@gmail.com (B. Oberle).

[1] Abbreviations: coarse woody debris (CWD), specific gravity (SG), moisture content (MC), decay class (DC).

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While decay classification systems can be fast and accurate, they also have several limitations. First, the number of classes and the criteria used can vary between surveys, impeding comparisons (Mäkipää and Linkosalo, 2011). Second, determining the decay class requires the judgment of a trained surveyor which can introduce subjectivity and variation depending on experience (Larjavaara and Muller-Landau, 2010). Finally, as an ordinal representation of a continuous process (decay), decay classification may lack the resolution necessary to parameterize important processes that govern CWD dynamics.

Noting these limitations, Larjavaara and Muller-Landau (2010) recommended an alternative method for quantifying dead wood density in permanent tropical forest plots based on a comparison of four methods. In addition to a decay classification system, they implemented three methods for measuring the resistance of CWD to a penetrating force. The most accurate and repeatable method in their system was based on a dynamic penetrometer: a steel stylus attached to a 1 kg slide hammer. After repeatedly dropping the hammer from a fixed height, the penetration depth of the stylus was correlated to sample density and differed little among operators. Based on this result, the low cost of materials and minimal disruption of the wood during measurement, they recommended using a dynamic penetrometer to estimate dead wood density in CWD surveys for carbon accounting.

While developed as a more accurate and repeatable alternative to decay classification, the dynamic penetrometer does not directly measure density. Instead, it measures the volume of dead wood displaced by repeated application of a transverse penetrating force. This measurement principle is complementary to that of a routine materials science test. The Janka test quantifies the force necessary to embed a steel sphere 11.28 mm in diameter to half its length in another material (Green et al., 2006). The resulting value, hardness, is well known in the wood engineering literature for its effects on the performance of wood products such as flooring (Wiemann and Green, 2007). For intact wood, Janka hardness strongly correlates with density (Kretschmann, 2010). However, the relationship between hardness and density changes with several factors which are likely to vary during a CWD survey: wood moisture content, interspecific differences and degree of decay. Understanding how these factors influence penetrometer measurements could improve their accuracy and provide insights into how wood mechanical properties change during decay.

Moisture content (MC) can influence the relationship between wood hardness and density. The ratio of wood density to that of water (specific gravity, SG) tends to decrease linearly with increasing MC from oven dry (0% MC) to the fiber saturation point (typically near 28% MC). Janka hardness, in contrast, decreases as a power function of increasing MC up to an inflection point between 20% and 28% MC (Wiemann and Green, 2007). In natural settings, dead wood MC can vary across this range depending on air humidity, direct sun exposure, ground contact and saprobe activity (Glass and Zelinka, 2010). Consequently, changes in dead wood MC may change hardness and therefore penetrometer measurements independent of changes in density.

Second, interspecific differences in wood density explain most but not all variation in hardness. Hardness also depends on other features of wood chemistry and anatomy, from cellulose microfibril angle to void space distribution, that vary greatly among species (Tze et al., 2007; Winandy and Rowell, 2005; Zhang, 1997). For example, angiosperm wood tends to be denser and therefore harder than conifer wood (hence the common distinction of hardwood versus softwood). However, the empirical relationships between SG and hardness differs between these two groups (Wiemann and Green, 2007), reflecting division-level differences in wood construction. Taxonomic differences in wood construction may persist as wood decays through interactions with specialized saprobes contributing variation to the relationship between hardness and density depending on species composition.

Finally, mechanical properties can change idiosyncratically as wood decays. During the earliest stages of decay, wood may lose mechanical strength more quickly than density (Curling et al., 2002). Wooden stakes deployed in northern forests lost surface hardness after only three months even though mass loss was barely detectable (Jurgensen et al., 2006). While hardness may initially decline more quickly than density, CWD hardness can later increase. Under some conditions, dead wood develops an extremely hard, decay-resistant outer shell (Spaulding and Hansbrough, 1944). This phenomenon, known as case hardening, has been variously attributed to physical changes that result from exposure to sunlight and extreme temperature (Harmon et al., 1995), chemical properties of species with durable wood (Pyle and Brown, 1998), and the legacy effect of decay while suspended (Spaulding and Hansbrough, 1944). Whatever the cause, case hardened wood decays slowly and can be retained in forests much longer than other CWD (Harmon et al., 1986).

The impacts of moisture and species differences on the relationship between density and hardness as wood decays have important implications for estimating CWD biomass and understanding its dynamics. We examine how wood mechanical properties change during decay in a central North American hardwood forest by conducting penetrometer measurements across a range of settings. First, we conducted a lab experiment mimicking the standard conditions of the Janka test, but using experimentally decayed wood for samples and the penetrometer as the testing device. Then we conducted a field experiment during which we relaxed standards to more closely resemble the conditions likely to occur in the field. Finally, we conducted a field survey on naturally recruited and decayed wood.

Our tests shared two complementary goals: first to analyze how penetrometer measurements vary with factors known to influence hardness of intact wood and second to evaluate how well penetrometer measurements perform as indices of dead wood density. With respect to the first goal, we expected that variation in penetrometer depth depends on four predictors: (1) SG, (2) MC, (3) species and (4) degree of decay. Due to the complementarity of measurement principles (penetrometer measurement equals distance given fixed force, while hardness equals force given fixed distance), we expected that effects of the first three predictors are similar in magnitude but opposite in sign to their known effects on Janka hardness of intact wood. Specifically, we expected penetrometer depth to decrease in samples that are denser, drier and derived from species with harder intact wood. Furthermore, we expected the relationships among these factors to change through time as wood decays. With respect to the second goal, we expected that penetrometer depth explains more variation in dead wood density than other factors across a range of measurement conditions.

2. Material and methods

2.1. Study site

We investigated how mechanical properties change during wood decay at the Tyson Research Center near St. Louis Missouri, USA. This site is located on the northern border of the Ozark Highlands ecoregion of east central North America. Approximately 85% of the site consists of forests on steep limestone ridges that are dominated by oak (*Quercus*) and hickory (*Carya*) species. Climate at the site is typical of a continental temperate deciduous forest, with average annual temperature and precipitation of approximately 14 °C and 103 cm respectively.