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Density and Specific Gravity Metrics in Biomass Research

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Abstract

Following the 2010 publication of *Measuring Wood Specific Gravity… Correctly* in the American Journal of Botany, readers contacted us to inquire about application of wood density and specific gravity to biomass research. Here we recommend methods for sample collection, volume measurement, and determination of wood density and specific gravity for use in biomass studies. We include discussion of the effects of wood deterioration and reliance on published density metrics. In addition, we note pitfalls associated with standard methods, limitations of using densities in biomass estimates, and interpretation of international databases giving wood densities.

Whether it is standing biomass, coarse woody debris, reliance on published density metrics, or interpreting international wood standards, the application should drive the methodology, and the methodology is critical to the results and interpretation. Wood-specific gravity, which is unitless, refers to oven-dry mass per volume at a specified moisture content, relative to the density of water. It is defined differently from wood density, which is mass per unit volume under any moisture condition. The moisture content of wood affects mass directly and volume indirectly through shrinkage or swelling, so in research "wood" is ambiguous without a specified moisture condition. Therefore, for all applications of density or specific gravity, the measurement conditions should be determined and published along with the density metrics.

Keywords: biomass, coarse woody debris, density, international standards, specific gravity

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Introduction

In a recent *American Journal of Botany* article, we reiterated the distinction between wood density, which is wood mass/wood volume, and wood specific gravity (SG), which is oven-dry wood mass/wood volume/density of water (Williamson and Wiemann 2010). Because wood shrinks as it dries, the SG of wood can be determined at different wood volumes depending on its moisture content (MC): green volume when saturated with water, oven-dry volume when the MC is zero, and volume at a specified MC for intermediate values. These are typically referred to as basic SG, oven-dry SG, and SG at a specified MC, respectively. Wood mass for SG is always determined oven-dry, i.e., at a MC of zero. For wood density, the mass and volume are determined at the same MC, although the hybrid term "basic density" is defined as oven-dry mass divided by green volume. For any wood sample, the numerical values of SG and density differ from one another as MC varies above the oven-dry condition.

Clarifying these definitions and identifying errors in recently published ecological studies (Williamson and Wiemann 2010) triggered queries about some applications of SG metrics. Many of the queries were focused on biomass research and international conventions. This is no surprise, given the importance of the global carbon cycle.

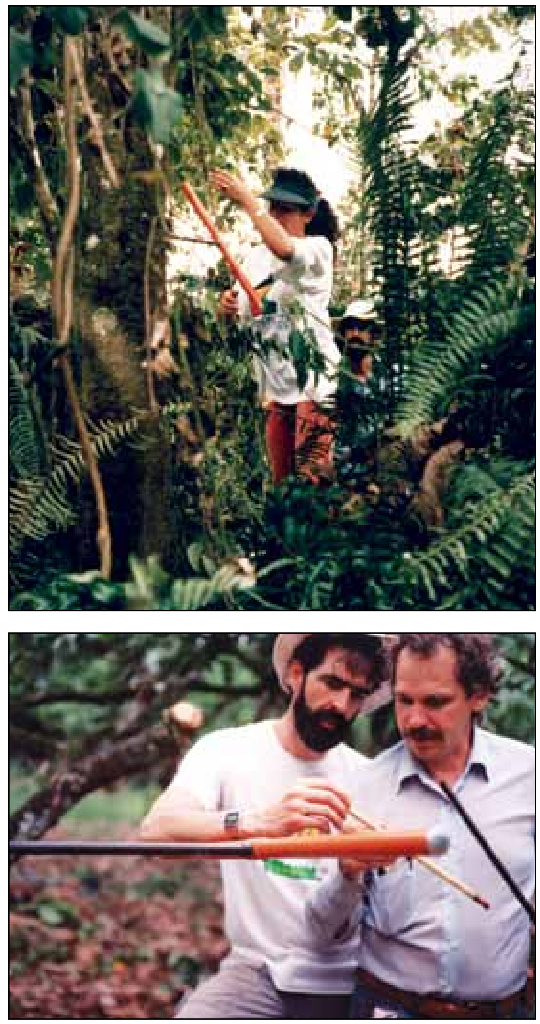

Figure 1. (a) Extraction of a core from *Ochroma pyramidale* using an increment borer in Costa Rica. (b) Verifying a bark-to-pith core.

Density and SG in Biomass Estimation

Woody biomass of standing trees can be determined from estimates of tree volume, based on diameter and height measurements, and basic density or SG (Wenger 1984). Many biomass studies state that wood volumes are multiplied by "basic SG" when they mean "basic density." The product of volume and density is a mass, whereas the product of volume and SG is a volume because SG is unitless. Biomass studies can "weight" wood volumes by basic SG and then convert volume into mass by multiplying by the density of water (1g/cm^3). Or they can use the hybrid metric of basic density but not referenced as SG. SG of wood and bark in standing trees can be estimated from samples taken with increment borers (Fig. 1a). Best estimates of wood SG or density will include all of the wood, from pith to bark (Fig. 1b) and along the height (Rueda and Williamson 1992) and will be weighted to represent the whole tree (Williamson and Wiemann 2010). Likewise, if bark is to be considered, it should include both inner bark (phloem) and outer bark (periderm). Biomass can be determined more precisely by harvesting trees and determining species-specific regression equations for a site or region (Nelson et al. 1999, Nogueira

Figure 2. Measuring volume of coarse woody debris with a reel tape measure and calipers in Wisconsin.

Figure 3. Small coarse woody debris in the Fernow Experimental Forest, West Virginia.

et al. 2008). If a tree is felled, an unbiased measure of its density or SG can be obtained from wedges or complete disks.

Density of decomposing wood such as coarse woody debris (CWD) can be determined most accurately by measuring mass and volume directly, rather than borrowing density or SG values from the literature. In practice, the volumes of CWD are estimated from linear measurements in the field (Fig. 2) and a sub-sample taken to determine density. The measured volume of CWD should be multiplied by the sub-sample's oven-dry mass divided by the sub-sample's volume at field moisture conditions. Volume of a decayed sub-sample should be determined the same way that volume of the CWD was determined, usually from linear measurements, not from a different method such as water displacement, for several reasons: the methods may give different estimates because wood that is not saturated will absorb water during water displacement unless it is wax coated, and wood volume changes as wood decays and voids are created in the wood. Accurate linear measurement of a sub-sample requires that it be machined to a regular shape with right-angle corners (*ASTM Standards* 2010; D2395-07a, Test Method A). Mass should be determined after drying at 103 °C to constant weight. (Also, mass should be measured before drying to be able to calculate MC of the debris.) Some SG measurements of CWD are based on drying at only 65 °C to reduce loss of volatile compounds at high temperature. A study by Adams and Owens (2001) of CWD in a temperate hardwood forest showed that oven-dry mass was within 1% of the mass of wood dried at 65 °C.

Wood from moist forest floors will often be saturated, but debris at many sites is not saturated (Fig. 3). Decaying wood, even if apparently preserved by submersion, may exhibit exaggerated shrinkage with concomitant SG changes (Borgin et al. 1979). Given that CWD is always in some stage of decay, mass and volume determined from subsamples will provide a more accurate measure of density than the published values for species (Harmon et al.1986).

Adams and Owens (2001) partitioned CWD of 21 species found on the Fernow Experimental Forest into three decay classes: 1) wood firm, 2) wood soft in some places, and 3) wood soft throughout. Across all species, mean SG decreased by nearly 50% from class 1 to class 3.

Measurement problems caused by decomposing wood are not confined to debris. In addition to the obvious problem of extracting an increment borer from a hollow or rotten tree, biomass of standing timber can be overestimated because of internal decay.

Unlike decay, wetwood is the result of anaerobic bacterial action in a living tree. The presence of wetwood in and of itself does not require a density adjustment. Wetwood frequently accumulates methane gas under pressure. In such cases, coring wetwood converts the end of the increment borer into a gas valve, as in Figure 4 showing the ignited gas from a bored *Bursera simaruba*. Unexposed wetwood does not decay rapidly, nor does it lower the wood SG, because the bacteria feed on the cell contents, not cell walls. However, when a tree containing wetwood dies, decay follows rapidly (Shigo 1986) and may affect the wood density.

Relying on Published SG Values in Biomass Research

Sources of published SG values vary from individual studies to large databases. Local sources often provide detailed data of methodology, specifying exact moisture conditions and drying temperatures associated with measurements. Compilations and databases are handier but do not ensure that standard or even equivalent methods have been employed among species in the same database. The Global Wood Density Database is currently the most comprehensive compilation of wood basic density (oven-dry mass/green volume) with over 16,000 values for more than 8,000 species. Initially published by Chave et al. (2009), it is now publicly accessible through *Dryad Digital* (www.datadryad.org/repo/handle/10255/dryad.235) and provides density values with citations (Chave et al. 2009, Zanne et al. 2009). Values for bark are harder to find, but Miles and Smith (2009) have compiled SG values for 156 North American tree species. Their range for bark (0.25–0.72) is almost the same as their range for temperate wood (0.29–0.78), so using a single value for bark can be as problematic as a single value for wood. When searching for SG or density data, it is often easy to start with a global or regional database and then to proceed to original data sources if verification of measurement conditions is needed.

Published SG values often provide an average from various sources, although the trees averaged may not be a random sample. The above-mentioned *Dryad Digital* database lists 14 basic density values for *Ochroma pyramidale* (Cav. ex Lam.) Urb., with a range of 0.100 to 0.220 and a mean of 0.158 g/cm^3. The SG of wood of this species increases from about 0.04 to 0.40 from the pith to the bark in large trees (Whitmore 1973), so the values in the database would seem to represent sampling of small-diameter trees. Unfortunately, the actual wood samples for many published values have been discarded, making verification impossible. Even where wood samples are available, as in wood collections, they often lack accompanying herbarium vouchers. Nevertheless, thanks to numerous wood samples, outliers have little effect on the "mean" SG values of common species, and variation in SG among species is much greater than variation within a species.

Wood SG for a given species can vary geographically, partially a result of climatic variation (e.g., Whitmore 1973, Wiemann and Williamson 1989b), and such variation is unlikely to be recorded in large compilations of specific gravities for a species, although a species SG may be listed as "variable." Therefore, use of a single SG value to characterize each species globally may be appropriate for comparison of large datasets (e.g., Wiemann and Williamson 2002, Chave et al. 2006, 2009), but for single site studies, local SG values are likely to provide more meaningful analyses (e.g., Poorter et al. 2006, Wright et al. 2010).

Finally, SG variation within trees is large, especially in tropical pioneers (Wiemann and Williamson 1988, 1989a,b, Omolodun et al. 1991, Rueda and Williamson 1992, Parolin 2002, Nock et al. 2009). The SG for the tree depicted in Figure 5 varied from 0.07 (near the pith) to 0.45 (near the bark). The diameter of this tree was 146 cm, and the length of the increment borer from tip to handle was 81 cm. Surprisingly, it took only three attempts to reach the center of this tree. When SG varies linearly from pith to bark, as it does in *Ceiba pentandra*, an estimate of the cross-sectional SG can be found at one-sixth of the diameter inside the bark (dib) (Williamson and Wiemann 2010). For the tree shown, a weighted basic SG average of all 1-cm bark-to-pith segments gave a value of 0.384, whereas the basic SG of the wood at one-sixth of the estimated dib (23–25 cm from the cambium) was 0.381 (Wiemann and Williamson, unpublished data). An analysis of the accuracy of single-value estimations of SG is discussed in Wiemann and Williamson (2012).

Use of a single SG value may be appropriate for estimating standing biomass, although species-specific regressions of biomass on diameter are more accurate (Nelson et al. 1999). In wood decomposition studies, it may prove useful to determine initial densities for various components and sizes of tree debris because wood density of living trees varies by tree age and by location along trunks and limbs (Koch 1985, Nock et al. 2009, Williamson and Wiemann 2011).

Standard Methods in Biomass Research

U.S. foresters traditionally rely on ASTM Standards and the Forest Products Laboratory for guidance in determining wood properties, but standard sources become outdated. For example, measuring the volume of small wood samples has been problematic historically in density determinations. The Forest Products Laboratory published an endorsement of the maximum moisture content (MMC) method for

Figue 4. Adjusting the flame from ignited methane streaming from the wetwood zone of a large *Bursera simaruba*.

Figure 5. Extraction of a core, using a large-diameter increment borer, for pith-to-bark SG measurements from a large *Ceiba pentandra* in Sarapiquí, Costa Rica.

Figure 6. Measurement of the green volume of an increment core segment by water displacement.

estimating SG, a method that avoids volume determination (Smith 1954). Although still in use today, the method as published does not account for the high density of bound water versus free water (MacLean 1952). Bound water is denser than free water because of compaction of the adsorbed water (Skaar 1972). In the MMC method, void space in green wood must be filled completely by water. Although the air content of green wood is highly variable across species, it averaged about 20% in one study (Gartner et al. 2004), so a vacuum would have to be drawn on a submerged sample that is small enough to permit removal of all residual air. It is often necessary to oscillate between vacuum and pressure under water to remove all the air (Skaar 1972). The MMC method requires a value for the specific gravity of wood substance, which is not constant among species and may be affected by extractive content; Smith (1954) gives a range of 1.50 to 1.56, with an average of 1.53.

Yet another volumetric misguidance comes from the *ASTM Standards* (2010). Standard D2395-07a, Test Method B, describes wood volume determination by water immersion. In Modes I and IV, wood volume is observed directly as displacement in a water-filled container or volumetric cylinder, whereas in Modes II and III, volume is obtained from the weight of water displaced. Although the standard includes the final caveat that "The precision and bias of these test methods for determining specific gravity are being established," it is our experience that measurement of volume directly is less precise than measuring the weight of water displaced. Given that a balance is needed anyway to determine mass for the SG determinations of the standard, it is difficult to explain the inclusion of the direct volume measurement procedures. Figure 6 shows the accurate measurement of the volume of a small sample using water displacement (Mode II).

SG and density standards outside the United States vary across continents, so results should be interpreted carefully from the methods. For example, French standards historically have characterized tropical woods by density at 12% or 15% moisture content, not by basic SG (Sallenave 1955). In practice this is often accomplished by drying samples at 20 °C and 65% relative humidity.

International nomenclature is often confusing, especially under the metric system (CGS units), where basic density (in g/cm^3) and basic specific gravity have the same numerical value. Therefore, it is wise to ignore cognates and carefully read the methods of each study. For example, francophone countries use "densité," "densité basale," "masse volumique," and "poids spécifique" somewhat interchangeably. Failure to carefully read the methods led Williamson and Wiemann (2010) to misinterpret the drying temperature in Ruelle et al. (2007) as 65 °C when it was 20 °C and 65% relative humidity. Analogous cognates appear in Neotropical studies published in Portuguese and Spanish. It should also come as no surprise that scientists abroad have difficulty interpreting U.S. nomenclature, especially where standard practices differ. Some of the inconsistencies we enumerated earlier (Williamson and Wiemann 2010) were made by scientists trained outside the United States and may have resulted from different standards across continents.

Summary

SG of wood or bark is defined as oven-dry mass per unit volume at specified moisture content, relative to the density of water. This is different from density, which is mass, including moisture, per unit volume at any moisture content. Moisture in wood affects mass directly and volume indirectly through shrinkage or swelling, so in research it is essential to specify moisture conditions and methods employed to determine mass and volume. Likewise, careful reading of methods is critical to avoid misinterpretation of studies that involve standing trees, wet or dry coarse woody debris, partially decayed biomass, previously published or tabulated data, or international standards.

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