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BRIEF COMMUNICATION

Measuring wood specific gravity…Correctly[1]

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The specific gravity (SG) of wood is a measure of the amount of structural material a tree species allocates to support and strength. In recent years, wood specific gravity, traditionally a forester's variable, has become the domain of ecologists exploring the universality of plant functional traits and conservationists estimating global carbon stocks. While these developments have expanded our knowledge and sample of woods, the methodologies employed to measure wood SG have not received as much scrutiny as SG's ecological importance. Here, we reiterate some of the basic principles and methods for measuring the SG of wood to clarify past practices of foresters and ecologists and to identify some of the prominent errors in recent studies and their consequences. In particular, we identify errors in (1) extracting wood samples that are not representative of tree wood, (2) differentiating wood specific gravity from wood density, (3) drying wood samples at temperatures below 100°C and the resulting moisture content complications, and (4) improperly measuring wood volumes. In addition, we introduce a new experimental technique, using applied calculus, for estimating SG when the form of radial variation is known, a method that significantly reduces the effort required to sample a tree's wood.

Key words: increment borers; moisture content; oven drying; tree cores; Wiemann approximation; wood density; wood specific gravity. The abstract and key words are also provided in Spanish with the online version of this article.

Different tree species allocate different quantities of wood to produce their trunks. Fast-growing, short-lived species produce trunks with less wood and more space filled with water or air. Long-lived, slow-growing species produce trunks with more wood and less space, resulting in greater strength and longevity. Trunk support can be quantified by measuring the specific gravity of trunk wood.

In the last few years, wood specific gravity (SG) has become a popular topic as plant biologists search for broad-spectrum functional traits and determine their ecological and evolutionary significance (Muller-Landau, 2004; Chave et al., 2006, 2009; King et al., 2006; van Gelder et al., 2006; Swenson and Enquist, 2007, 2008). Specific gravity has been acclaimed as the integrator of wood properties in the "wood economics spectrum" given its importance in structure, storage, and translocation (Chave et al., 2009). In addition, SG is the primary variable in the estimation of biomass to assess global carbon stocks (Brown and Lugo, 1992; Fearnside, 1997; Chave et al., 2005; Nogueira et al., 2005; Malhi et al., 2006; Keeling and Phillips, 2007; Nogueira et al., 2007, 2008a, b; Baker et al., 2009).

While these developments have expanded our knowledge and sample of woods, especially the lesser-known tropical species, it has become increasingly apparent that the methodologies employed to measure wood SG have not received as much attention as SG's ecological importance. Given the rate of information spread in the electronic age, it should be no surprise that a number of recent studies that have measured SG incorrectly have had their methods adopted and cited by other authors. While many of the errors can be attributed to ecologists new to wood science, representative sampling is sometimes still a problem in wood science as well. Here, we reiterate some of the basic principles and methods for measuring the SG of wood in hopes of clarifying past practices of foresters and ecologists, and we identify some of the prominent errors in recent studies and their consequences. In addition, we propose a new method for estimating SG when the form of radial variation is known.

Wood samples and tree SG estimates—Historically, wood samples were taken as disks from the lower portion of the bole and, more recently, as increment borer samples. Radially from pith to bark, wood SG may remain constant or increase dramatically, moderately, or slightly, or decrease. In many tropical pioneer and second growth species, SG increases 4-fold or more (Wiemann and Williamson, 1988, 1989a, b). In contrast, SG in some mature forest species increases only slightly or may even decrease, for example, when heartwood has a higher SG than sapwood due to the presence of secondary compounds. Given the possibility of radial variation, there is no way to characterize the SG of the entire stem cross section without a disk of wood or a complete pith to bark core. Outside of experimental plantings, trees are rarely cut for disks today, although trees cut for other reasons offer opportunities for disks.

A core can provide a complete wood sample if it stretches from the pith to the bark. 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.

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A pith to bark core overrepresents the proportion of wood toward the pith, so an area-weighted mean of segments of the core should be employed to determine the average wood SG for an individual tree, not simply measuring SG of the core itself (Table 1: King et al., 2006; Saldaña-Acosta et al., 2008; Swenson and Enquist, 2008; Sungpalee et al., 2009). If the core has been divided into segments for SG determinations, then the area of the ring of each core segment can be determined and the weighted mean specific gravity, G_{mean}, calculated, as demonstrated by Muller-Landau (2004). Alternatively, if the form of the radial variation is known, then a function that describes the change in specific gravity $G(r)$ as the radius r increases can be integrated, assuming a circular trunk shape:

$$G_{mean} = 2\pi\int_0^R rG(r)\,dr / 2\pi\int_0^R r\,dr, \qquad \text{(Eq. 1)}$$

where R is the tree radius. Minor radial changes can be ignored, but monotonically increasing or decreasing specific gravity functions require weighting. If the changes are approximately linear then the function assumes the form

$$G(r) = gr + G_p, \qquad \text{(Eq. 2)}$$

where g is the slope or rate of change of SG with radius r (cm^{-1}), and G_p is the specific gravity at the intercept or pith. When Eq. 2 for $G(r)$ is substituted into Eq. 1, the integration formula for G_{mean} reduces to

$$G_{mean} = G_p + (2/3)gR. \qquad \text{(Eq. 3)}$$

This method requires that the rate of radial change, g, and tree size, R, be reported as well as G_{mean} because R will affect the G_{mean}. It follows that short cores or samples that include only wood near the bark can misrepresent the cross-sectional G_{mean} (Table 1: Poorter et al., 2006; Swenson and Enquist, 2008).

Likewise, a sample from outside the trunk, such as branch wood, is not a measure of trunk wood SG. Branch wood is extremely variable, and its relation to trunk wood is species-specific and often individual-specific (Fegel, 1938, 1941; Okai et al., 2004; van Gelder et al., 2006; Swenson and Enquist, 2008; Patiño et al., 2009). It is unlikely to represent the range found in trunk wood. Furthermore, the SG of branch wood can be strongly affected by juvenile wood in young branches or by tension/compression wood in older branches. Obtaining "clean" branch samples is often difficult and varies among species, within individual trees and within branches. Swenson and Enquist's (2008) recommendation to use branch wood SG to estimate trunk wood SG, based on one or two trees per species, is a poor justification for improper sampling. Of course, wood samples should contain neither bark nor pith (Table 1: van Gelder et al., 2006; Swenson and Enquist, 2008), although all these separate parts—branches, bark, pith—may be the subject of separate investigations or whole stems may be studied.

The consequences of incomplete wood samples are substantial because samples are supposed to represent the entire tree. Short samples from the outer portion of the trunk may misrepresent a tree's SG by 100% or more in species exhibiting radial changes in SG.

The number of trees required to sample a species in a given ecosystem depends on the variability within the species. In general, five trees, healthy and straight individuals, are a minimum (Cornelissen et al., 2003). One or two individuals are inadequate

TABLE 1. Some recent studies utilizing wood SG and their common errors: oven drying at less than 100°C, using SG and density interchangeably, and various sampling problems.

Author(s)	Publication	Year	Oven dry temp. (°C)	Mixed SG and density	Sampling problems
King et al.	Journal of Ecology	2006	67–71	yes	Unweighted cores 0.515 cm borers
Martínez-Cabrera et al.	American Journal of Botany	2009	75	no	Outermost wood Rehydrated samples
Muller-Landau	Biotropica	2004	50, 65, 60–70, 70	no	0.515 cm borers.
Poorter et al.	Ecology	2006	70	yes	Short samples, 2 cm
Ruelle et al.	Annals of Forest Science	2007	65	yes	
Saldaña-Acosta et al.	Acta Oecologia	2008	70	no	Unweighted cores
Sungpalee et al.	Journal of Tropical Ecology	2009	85	yes	Unweighted cores 0.515 cm borers
Swenson and Enquist	American Journal of Botany	2008	60	no	Inaccurate volumes Unweighted cores 1–2 trees/species
van Gelder et al.	New Phytologist	2006	70	yes	Included bark and pith
Wright et al.	Annals of Botany	2007	not given	no	Methods not given
Classic wood references					
	Annual Book of ASTM Standards, D2395-07a	2009	103 ± 2		
	Forest Products Laboratory, Wood Handbook, Chap. 12	1999	101–105		
	Principles Wood Sci. & Tech., Kollmann and Côté	1968	100–103		
	Science and Technology of Wood, Tsoumis	1991	103 ± 2		
	Technologie des Holzes und der Holzwerkstoffe, Kollmann	1951	100–103		

because variability among individuals remains unknown (Table 1: Swenson and Enquist, 2008).

An alternative method for estimating SG: the Wiemann approximation—Recently, at the Forest Products Laboratory, a new method of estimating SG, still in the experimental stage, has been applied to increment cores when the form of radial variation is known for a given species at a given site. From the known form of radial change in SG, we can mathematically calculate the point of approximation, ř, on the radius, where the specific gravity, $G(\check{r})$, equals the tree average, G_{mean}. For the case in which SG changes linearly with r, we equate the solution for G_{mean} and $G(\check{r})$.

$$G_p + (2/3)gR = g\check{r} + G_p. \quad \text{(Eq. 4)}$$

Algebraic reduction gives the following value for the point of approximation:

$$\check{r} = (2/3)R. \quad \text{(Eq. 5)}$$

Therefore, the SG at 2/3 of the tree radius estimates the tree mean. Accordingly, the tree diameter can be measured and then the tree bored from the bark a little more than 1/3 the radius (1/6 the diameter). The SG of the wood at the end of the core would approximate the tree mean SG, given a slight adjustment for the thickness of the bark. Boring trees 1/6 of their diameter is considerably easier than obtaining pith to bark cores. Tree asymmetries, especially common on slopes, may require additional adjustments. Likewise, SG variation with height along the bole will require an adjustment for total trunk SG, but height variation is rarely known (Rueda and Williamson, 1992).

To date, the Wiemann approximation has worked well, especially with large diameter trees whose SG is linear across the radius, increasing, decreasing, or no change (data not shown). Other forms of radial change can be approximated by nonlinear functions to determine the point of approximation. Unfortunately, this method requires prior knowledge of the form of the radial variation in SG, and in most cases, this form is not known and must be investigated on site by pith to bark cores for each species of interest. However, as research accumulates, tables of species' radial variations will become available, just as tables of species' SG are available. Furthermore, forms of radial variation will eventually be characterized by functional types and by phylogeny, thereby providing some generalities. For example, in our prior studies of pioneer species of lowland wet forests in Costa Rica, the form of radial increases was generally linear, so we characterized species-specific radial variation by a linear regression equation of SG on radial distance and the actual radius (Wiemann and Williamson, 1988, 1989a). Some forms are well known especially for commercial species. For example, several decades ago, Panshin and de Zeeuw (1980) summarized the trends found in published studies for more than 80 angiosperm and gymnosperm species.

Most community studies where SG profiles are determined for forests or geographic regions use a single value for each species without regard to radial variation. By default, such studies assume there is no radial variation or that published tabulations, somehow averaged over various wood samples, contain an approximation that is weighted correctly. The magnitude of errors due to regional variation in SG is largely unexplored although variation across biomes is known for a few species (Whitmore, 1973; Wiemann and Williamson, 1989b).

Specific gravity is not density—The specific gravity of wood is defined as the density of wood relative to the density of water (ρ_{water}), which is 1.000 g·cm^{-3} at 4.4°C; therefore, SG is unitless. The SG of wood depends on the relative proportions of cellulose, lignin, hemicellulose, extraneous components, gas, and water (moisture content or MC). Because the MC of wood can vary greatly, foresters standardized several specific gravity measures to facilitate comparisons within and across species, all of which are based on the oven dry (101–105°C) mass of the wood:

$$\text{Basic SG}: G_b = \text{oven dry mass} / \text{green volume} / \rho_{water}$$

$$\text{Air dry SG}: G_{mc} = \text{oven dry mass} / \text{air dry volume, at specified MC} / \rho_{water}$$

$$\text{Oven dry SG}: G_o = \text{oven dry mass} / \text{oven dry volume} / \rho_{water}$$

Each SG uses two moisture content states, one for mass and one for volume. As oven dry mass is used in the numerator of all the SG standards, only the state of the volume changes. Strictly speaking from the standpoint of physics, only oven dry SG is a true specific gravity where mass and volume are determined with wood in the same state.

Wood volume varies according to the MC because wood shrinks as it is dried. Shrinkage from green to oven dry varies from about 4% (teak, *Tectona grandis*) to 20% (African ebony, *Diospyros* spp.) among imported commercial woods (Forest Products Laboratory, 1999). Higher SG woods shrink more than lower SG woods, and SG extremes will shrink less than 4% and more than 20%.

For air dry SG, the MC must be specified. Common values include 8, 12, and 15%, varying by custom according to geographic region. These differences arose because foresters historically needed a value for lumber that was air-dried for local use and as such had an equilibrium moisture content (EMC) determined by local air temperature and humidity. EMC values, based on temperature and humidity during drying, are available from the Forest Products Laboratory's Wood Handbook, Chapter 12 (1999) and can be used in the conversion of G_{mc} to G_b or G_o. When obtaining values from the various sources in the literature to compare SG across regions, particular care must be exercised to convert specific gravities to a common standard, usually basic specific gravity; otherwise, gross errors can occur. Oven dry SG should be 4–20% greater than basic SG due to 4–20% shrinkage for those imported commercial woods. Air dry specific gravities will be intermediate.

Basic SG most closely corresponds to an ecological trait because it is the dry biomass in a unit volume of green wood. Ecologists expect and have shown that there is a trade-off between the volume of wood produced and the basic SG of wood produced. This trade-off is related to other characteristics such as growth rates, first age of reproduction, mortality rates, longevity, and maximum tree height (Budowski, 1965; Williamson, 1975; Putz et al., 1983; Poorter et al., 2008; King et al., 2006; Chave et al., 2009).

Conversion formulas are available for these SG standards based on the MC of wood when its SG was measured. The best conversion formulas are species-specific, although they are unavailable for most tropical woods. Therefore, general formulas or tables that require input of the measured SG and the MC of

the measured wood are frequently used (Simpson, 1993; fig. 3.6 and table 3.7 in Forest Products Laboratory, 1999). There is some evidence that formulas for conversions of tropical woods differ slightly from formulas for woods outside the tropics (e.g., Sallenave, 1971).

A common mistake in recent publications is to fail to distinguish between SG and density (Table 1). Wood density is actually a measure of the mass of a wood per unit volume ($kg \cdot m^{-3}$ or $lb \cdot ft^{-3}$) and can be measured at any moisture content. Density is a measure of a wood's mass for practical purposes such as shipping or estimation of load. Some confusion arises because foresters also defined density standards analogous to SG standards, where oven dry mass is divided by oven dry, air dry, and green volumes for oven dry, air dry, and basic densities. Except for these density standards, wood densities have mass and volume determined for the same MC. The metric system values for the density standards are the same as those for the SG standards for a given wood, except the former have units and the latter are unitless (Simpson, 1993; Forest Products Laboratory, 1999).

Many ecological articles whose sampling methods are sound and whose results are reliable use SG and density interchangeably (e.g., Baker et al., 2004; Chave et al., 2008). Technically, this is a mistake but often of little consequence, where the methods have been clearly described. On the other hand, using "specific gravity" for wood whose mass includes some water because it was not oven dried properly is misleading. For example, describing "basic wood density" as dry mass at 70°C and volume green is confusing and ignores the true moisture content of the samples (Table 1).

Oven drying—An important common error in recent publications is oven drying wood at less than 100°C. Oven drying requires 101–105°C because wood contains bound water, in addition to free water. All bound water cannot be driven off at less than 100°C. Plant biologists commonly oven dry leaves or fruits around 60°C or 70°C because there is little bound water in fleshy plant parts and higher temperatures result in losses of low molecular weight organic compounds (Westerman, 1990; Pearcy et al., 1989). Expanding their studies to functional traits of wood, some plant biologists apparently continue to oven dry wood at similar temperatures (Table 1). Defining protocol for measuring functional traits, Cornelissen et al. (2003) recommend drying herbaceous stems at 60°C for 72 h or 80°C for 48–72 h and then extend the recommendation to woody stems. In contrast, because wood is mainly cellulose and lignin, containing substantial bound water and relatively small quantities of low molecular weight compounds, wood scientists almost universally oven dry wood samples at just over 100°C (Table 1). Drying to a constant mass at 101–105°C in a well-ventilated oven requires 24–72 h, depending on the sample size.

Foresters often speak of additional extraneous compounds as "extractables" because some of them can be dissolved and extracted. These compounds may affect wood mass and SG. Low molecular weight compounds may be volatilized by drying at temperatures above 100°C. For most woods, extraneous compounds make up less than 2% of the mass and can be overlooked, but for those species with higher concentrations extraneous content and SG can be reported separately, if oven drying and distillation are both performed on wood (Annual Book of ASTM Standards 2009).

Besides confusion, the greatest consequence of oven drying at less than 100°C is the lack of data on moisture content. Basic SG of these wood samples will never be known because the MC content of them was not determined. Such studies become stand-alone efforts, whose results cannot be compared to other studies based on specific gravity standards. Conversion formulas are useless because they require knowledge of moisture content of the woods dried at less than 100°C. Furthermore, the species' specific gravities can never be incorporated into global databases which are based on basic specific gravities. These international databases are increasingly important in global analyses, but only a fraction of the world's timbers have published SG values. For example, Chave et al. (2009) recently assembled comprehensive data on 8412 taxa, 1683 genera, 191 families worldwide—that is less than 10% of the global tree flora, estimated at 100 000 species (Oldfield et al., 1998). In fact, the Chave et al. (2009) list of 8412 taxa is roughly equal to the number of taxa threatened with global extinction (Schatz, 2009). The vast majority of unmeasured tree specific gravities are tropical, so contributing data from new species should be a priority among tropical researchers—a priority that requires measuring basic specific gravity correctly.

Volume measurement—Volume can be measured by water displacement or calculated from the dimensions of a sample block or core measured with calipers. Accurate water displacement requires immersion of the wood sample into a beaker of water loaded on a top-loading electronic balance. The wood sample is pressed below the water surface with the aid of a "volumeless" needle or insect pin. The volume of the wood is read accurately on the balance as the mass of the displaced water. Older methods of volume displacement in graduated cylinders or beakers where water levels are read by sight are much less accurate and increase variance in volume measurements (Table 1: Swenson and Enquist, 2008).

Citations and explanations—Whatever the procedure used on wood, researchers should explain their methods or carefully cite a source that they followed; otherwise, the readers are left in doubt, and the wood SG values cannot be entered into regional and global databases. For example, Sungpalee et al. (2009) oven dried their samples at 85°C and cited Chave et al. (2006) for methodology, but Chave et al. (2006) determined basic specific gravity correctly, drying their samples at 103°C. In some cases, the authors do not even detail their methods. For example, several of the articles cited in Table 1 took cores without specifying the diameter of their increment borers. Wright et al. (2007, p. 1006) simply sidestepped the matter entirely by stating, "In some cases the protocols for measuring the traits varied among sites; however, all efforts were made to standardize data so that they could be analyzed together." Perhaps wood SG was so poorly associated with other plant traits in their results because it was so inconsistently measured.

We presume that van Gelder et al. (2006) included bark and pith in their samples because their stated goal was to test sapling stem and branch samples for strength characteristics. To that end, we would concur in the inclusion of bark and pith. But the authors need to drop the use of "wood density" for samples that include more than wood and were oven dried at 70°C with volumes determined green. Preferable would be to define a "stem specific density" (e.g., Cornelissen et al., 2003), although more preferable still would be oven drying at 101–105°C and the use of "basic specific gravity" with clear reference to percentage bark and pith included.

Recommendation—We strongly recommend that researchers pay close attention to measurements of SG, especially if they expect their data sets to contribute to the extensive and growing body of information on global woods. We have cited only a few of the many studies with errors in measurements of SG, but we have focused on the most common errors. Interested researchers can read more about protocol in Chapter 3 of the Forest Products Laboratory's Wood Handbook online (http://www.fpl.fs.fed.us/products/publications/specific_pub.php?posting_id=16789; Simpson and TenWolde, 1999). We apologize both to those that we singled out for criticism and to those we failed to cite. Our goal is simply to raise the standards of the new wave of SG studies. Knowledge of tropical woods is in a second wave of discovery, following the last century's investigations primarily by foresters. Now come ecologists interested in all woods, not just commercial ones, armed with new tools, asking new questions on functional vs. phylogenetic diversity (Chave et al., 2006, 2009). We laud the evolutionary biologists who have embraced the forestry literature to bring new light to a large historical body of information on tropical woods. We hope that others will further develop these lines of investigation and do so as rigorously as possible.

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