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Cross-Section Mass: An Improved Basis for Woody Debris Necromass Inventory

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1 Introduction

Quantification of woody debris stocks is important for carbon budgets (Brown 2002) (Keith et al. 2009), fire ecology (Hely et al. 2000), and biodiversity conservation (Martikainen et al. 2000). Thus, woody debris are now often the subject of national inventories (Siitonen 2001, CFIC 2004) and have been the focus of significant methodological development and a wide variety of used methods have been described (Valentine et al. 2001, Bebber and Thomas 2003, Jordan et al. 2004, Affleck 2008).

The necromass of woody debris is typically estimated from the product of estimated volume and estimated density (dry mass per volume) (Harmon et al. 1986). We refer to this as *the volume-density approach*. Density is usually measured in terms of mass per volume of solid wood – that is, volume excluding void space, except for the tiny pores considered to be a natural part of the wood. However, the volume of logs is usually estimated assuming circular cross-sections of solid wood. The combination of density measurements per volume solid wood and volume measurements that include void space and assume circular cross-sections leads to biased estimates of necromass whenever there is void space and/or deviations from circular cross-sections – i.e., in most forests most of the time. These biases can be avoided through detailed measurements of void space and of noncircular logs (Keller et al. 2004, Grove et al. 2009) but such methods are time-consuming and infrequently employed.

We advocate an unbiased alternative approach to quantifying necromass of woody debris – an approach based on computing *cross-section mass*, the dry mass per unit length, of logs. Here, we first review the sources of bias in the volume-density approach as typically employed, and various methods for overcoming these biases within the context of that approach. We then present the cross-section mass approach, and show how it avoids the key challenges of the volume-density approach because it does not require estimation of volume. We close with a brief discussion.

Keywords biomass, coarse woody debris (CWD), deadwood, log, void space, nominal volume and wood density, carbon in woody detritus
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2 Volume-Density Approaches, Their Common Biases, and Methods to Overcome These Biases

What we refer to as volume-density approaches estimate necromass of woody debris as the product of estimated volume and estimated density. Density is measured on samples (usually of only a subset of logs) and in terms of dry mass per volume solid wood – what we refer to as *true density*. Thus, an unbiased estimate of necromass can be obtained by multiplying this true density with the volume of solid wood of woody debris per unit area, what we refer to as *true volume*. Unfortunately, accurate measurements of true volume are quite challenging, if not impossible, because of the presence of hollow logs, friable logs, and logs with non-circular cross-sections.

There are numerous methods to estimate the volume of woody debris per unit area. Here we focus on the line-intersect and plot-based methods as most commonly implemented. We refer to individual pieces of woody debris as logs. In the line-intersect approach, the diameters of all logs that intersect a transect are measured at the point of intersection of the transect and the central axis of the log (Warren and Olsen 1964) (in some publications "line-intercept"). Under the assumption that the cross-sections of all logs are circular, the total volume of woody debris per unit area (m^3/m^2), V, can be then estimated from

$$V = \frac{\pi^2}{8L} \sum d_i^2 \tag{1}$$

where L the total length of the transect (m) and d_i the diameter of the ith log of woody debris encountered (m) (See Appendix A for derivation). In the plot-based approach, the volumes of all logs within individual plots are estimated from dimensional measurements (lengths and diameters) and geometric equations (Rouvinen et al. 2002, Chao et al. 2009). Both approaches have their advantages and disadvantages.

Fundamentally, when aiming for volume, both the line-intersect and plot-based methods depend on estimating the cross-sectional area of logs encountered. (In the case of the plot-based methods, this is then multiplied by length to obtain volume.) In practice, cross-sectional area is generally estimated by assuming circular cross-sections and taking a single measurement of diameter – specifically, the width of the cross-section (measured with a caliper). This creates problems when cross-sections are not circular.

When cross-sections are elliptical rather than circular, use of a single diameter measurement leads to error and potentially bias. Cross-section widths may on average be larger than heights, as found in Sweden (Fraver et al. 2007) and in Panama (Larjavaara and Muller-Landau 2010), and therefore both volume and necromass are overestimated if only width is measured. On steep slopes, vertical log cross-sections are likely to be higher than they are wide, and thus volume and necromass are liable to underestimation if only width is measured (in the line-intersect approach; the same is true in the plot-based approach only if lengths are measured horizontally). These problems could be overcome by taking measurements of cross-section height in addition to cross-section width, and using the formula for the area of an ellipse to calculate cross-sectional area. An alternative approach, employed in Canada's National Forest Inventory (CFIC 2004), is to have field workers "estimate an equivalent diameter" (p. 42); this seems likely to lead to systematic error unless personnel are very carefully trained in such estimation.

Hollow logs and those with more irregularly shaped cross-sections present greater challenges. Estimation of their cross-sectional areas from diameter measurements under the assumption of circular, solid cross-sections leads invariably to overestimation. This can be corrected for if the amount of void space (relative to a perfectly circular cross-section) is accurately evaluated on samples, but methods for doing so are painstaking. For example, woody debris slices have been sawn out of logs, directly photographed (Keller et al. 2004) or first hand-drawn and then photographed (Grove et al. 2009) and finally cross-sectional area excluding the void space estimated from the photos, and representative samples of the non-void woody debris taken for drying, weighing and for volume estimation. Several of these tasks are very challenging even for solid wood and practically impossible for friable wood that breaks when handled (Fig. 1 left).

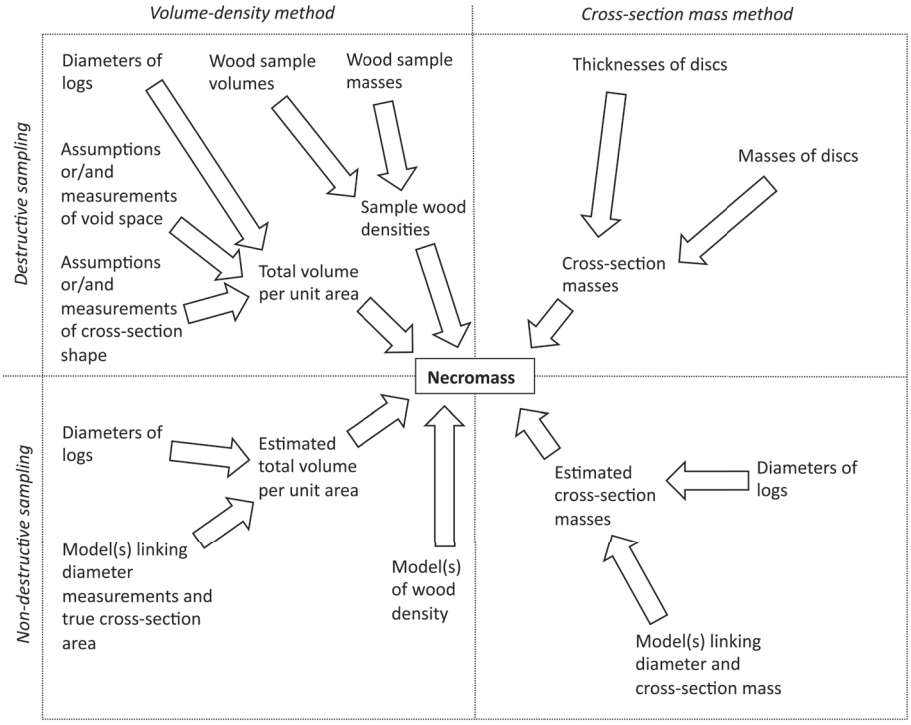

Fig. 1. Comparison of the traditional volume-density method (left) and alternative cross-section mass method (right). The measurements of wood sample volumes, void space and cross-section shape required in the traditional methodology with destructive sampling (top left) are difficult to conduct accurately, especially for friable logs. In contrast, the alternative methodology requires only measurements of mass and thickness of discs (top right), which are easy to measure even for friable logs. The data from these destructive samples form the basis of models that are used to estimate woody debris mass from diameter measurements (bottom panels), or potentially from diameter combined with other non-destructive measurements (e.g., decay class, not shown).

The challenges discussed above are all related to estimation of cross-sectional area and thus volume. Friable logs pose another type of problem, in that it is difficult to accurately estimate their density. The volume of wood density samples is typically estimated with water displacement, and for this purpose large, solid pieces are required; powdery samples lead to biased estimates of volume. Yet it is impossible to obtain appropriate solid samples from powdery logs. If friable logs are not sampled destructively, and instead assumed to have the same density as the remaining logs, then the average density is likely to be overestimated because density decreases and friability increases as decomposition advances (Harmon et al. 1986).

Ultimately, all these challenges relate to the need for consistency between the volume and density methods if these are to be combined to obtain an unbiased estimate of necromass. Volume inventories and density samples must both be unbiased samples of the same population: biases will result if, for example, hollow logs are excluded from the density samples while included in the volume inventories. And the same methods must be used to define and measure volume both on wood density samples and in the larger volume inventory. If the volume measurements of wood density samples exclude void space, then the measurements of total woody debris volume must also exclude void space. Even measuring diameter differently on samples relative to the

larger volume inventory has the potential to cause bias (e.g., measuring with diameter tape on logs from which wood density samples are taken, but with caliper as part of the larger volume inventory). It's easy to see how inconsistencies between methods can arise as researchers modify methods to achieve higher precision in individual phases of quantifying necromass, without realizing that such changes require corresponding adjustments in other parts of the methods.

Even where volume and density measurements are combined appropriately, the traditional approach combining measurements of true volume and true density is inherently problematic because of the difficulty of taking unbiased measurements of cross-sectional area of irregularly shaped, friable logs. Fortunately, unbiased estimates of necromass do not require measurements of true volume (of solid wood) and true density (dry mass per volume solid wood). Unbiased estimates of necromass can also be obtained by combining what we refer to as *nominal volume* – the volume of woody debris when assuming solid circular cross sections – and *nominal density* – the dry mass per unit nominal volume. Indeed, as we show in the next section, we can also obtain unbiased estimates of necromass without measuring any volume at all.

3 Alternative, Unbiased, Cross-Section Mass Approaches

The challenges of the volume-density approaches can be avoided by focusing necromass inventory methods instead on *cross-section mass*. Indeed, both line-intersect and plot-based inventories of necromass are based fundamentally on information on how much each log weighs per unit of its length, i.e., its cross-section mass. But in the volume-density approaches, cross-section mass is calculated as cross-sectional area times density, leading to all the previously discussed challenges of accurately measuring these. Cross-section mass of a log can instead be quantified simply and directly by cutting a slice, measuring its fresh thickness, and drying and weighing it (or a representative sample of it) – irregular cross-sections pose no problem. Friable logs also pose no special difficulty as thickness can be measured from the remaining log once the powdery sample has been bagged. This cross-section mass approach is analogous to a common way of estimating biomass of felled trees (Cairns et al. 2003) and has been previously suggested for woody debris inventory (Valentine et al. 2001).

When the cross-section mass approach is combined with line-intersect sampling, the necromass (kg/m^2), M, can be computed from the total length (m) of the transect, L, and the cross-section mass (kg/m) of the ith log of woody debris encountered, c_i:

$$M = \frac{\pi}{2L} \sum c_i \tag{2}$$

(See Appendix A for derivation). The cross-section mass need not be measured on every log – it can be estimated from the log's diameter (and potentially other properties) using functions calibrated with data from a subsample of logs, just as is commonly done with density in the volume-density approach.

The cross-section mass approach can also be combined with a plot-based inventory. In this case, the mass of each individual log or log section is estimated as its length times its average cross-section mass. The average cross-section mass can be estimated from one or more destructive samples, or from one or more sets of diameter measurements combined with equations calibrated from destructive samples. A taper function for diameter can be combined with two diameter measurements and a function relating diameter to cross-section mass to calculate the average cross-section mass. Just as when plot-based inventories are applied with the volume-density approach, irregularly shaped logs and taper that deviates from assumed functions present special challenges that can lead to biased estimates.

Taking and processing samples for estimating cross-section mass is relatively straightforward. In the case of the line-intercept method, slices should always be taken perpendicularly to the central axis of the log *and vertically*. If slices are not taken vertically, then cross-section mass will be underestimated whenever logs are not horizontal, as when they are on slopes. For the plot-based method, slices should be taken purely perpendicular to the axis along which log length

is measured, whether this is vertical or not. After a slice is taken, the fresh thickness of the disc should be measured with a small caliper (a good width is typically 20–60 mm for solid logs and up to 500 mm for friable logs). If the disc is too big to be transported for drying, fresh mass can be measured with a field scale (typically 0.1–5 kg) and a wedge shaped sample taken in a random direction and transported to the laboratory for oven-drying to obtain an estimate of water content and thus calculate dry mass of the disc. This dry mass is then divided by the disk thickness to obtain cross-section mass. For example, if the disc was on average 0.040 m thick, had a fresh weight of 8.0 kg, and the sample taken for drying was 50% water, then the dry mass of the whole disc is 4.0 kg, and the cross-section mass of the log is 4 kg / 0.04 m = 100 kg/m.

Cross-section mass can be modelled as a function of diameter and potentially other properties of logs for the purpose of estimating values for logs from which no samples are taken. In the simplest model, cross-section mass might be regressed on the square of diameter alone (i.e., assumed linearly proportional to nominal cross-section area). Mathematically this can be expressed as $c = b \cdot d^2$, where c is cross-section mass, b a parameter and d diameter. More precise and complex models could include additional variables, such as a second diameter measurement, decay class or e.g. a measure of hardness (Larjavaara and Muller-Landau 2010). Both simple and complex models will yield unbiased estimates of cross-section mass as long as both the destructive samples and the remainder of the inventory sample population or populations of logs with equivalent characteristics (for example, if they are in the same area at the same time and e.g. hollow logs are not excluded from data used for model development).

An alternative way to estimate cross-section mass on logs from which no samples are taken is to first estimate nominal cross-section area (assuming circular cross-sections and no void space) and nominal density, and then take the product. This leads to identical results, as the biases relative to true cross-section area and true density exactly cancel (see Appendix A). This method may be pedagogically easier for those schooled in the volume-density approach.

4 Discussion

In the past, the goal of much woody debris research was quantification of total volume (Harmon et al. 1986). With increasing interest in quantifying carbon stocks in recent years (Keith et al. 2009), the focus is now increasingly on necromass rather than volume. In practice, this shift has been accomplished by adding measurements of the density of woody debris to long-established methods for measuring volume.

Unfortunately, the resulting marriage of woody debris volume with wood density methods commonly results in biased estimates of necromass. Samples taken for wood density measurements are often a biased sample of the total population of logs (e.g., excluding friable logs), and their volume is often measured with different methods than are applied in the overall inventory (e.g., void space is excluded in volume measurements on the sample, but not in the rest of the inventory). It is easy to understand how this has come about: methods that have been adopted to increase the precision of measurements of density of solid wood ("true density") on samples have had the inadvertent effect of causing a bias in necromass estimates when combined with what are really "nominal volume" measurements from the inventory as a whole. We recommend use of the terms "nominal volume", "nominal density" (dry mass per nominal volume), "true volume", and "true density", to clarify this important distinction. Unbiased estimates of necromass can be obtained by combining nominal volume and nominal density, or true volume and true density, but not (as often done) nominal volume and true density.

We argue that woody debris necromass can be better quantified by focusing on the cross-section mass of logs, rather than on their volume and density, as previously suggested by Valentine et al. (2001). This completely circumvents the difficult problem of measuring the true cross-section area, or true volume of solid wood, on logs that are irregularly shaped, friable, and/or have void space – and leaves us with the much simpler task of measuring their mass per unit length. The cross-section mass approach simplifies field work and calculations, and removes the potential for bias due to inadequate consideration of void space and non-circular cross-sections.

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Appendix A
Derivation of Equations for Line-Intersect Approach for Volume-Density and Cross-Section Mass Methods

Fundamentally, the line-intersect approach to woody debris inventory calculates the average volume of woody debris by summing the cross-sectional area of woody debris encountered along the transects and dividing by transect length. Let A_i be the true cross-section area (m^2) of the ith log encountered, excluding void space and accounting appropriately for noncircularity, always measured perpendicularly to the central axis of the log. If all logs were oriented perpendicularly to the transect and the total length (m) of the transect is L, then the true volume of solid material of woody debris per area (m^3/m^2), V, could be calculated as

$$V = \frac{1}{L}\sum A_i \tag{A1}$$

However, for logs that are not perpendicular to the transect, the cross-section area along the transect – the relevant quantity to be summed – depends on the angle between the central axis of the log and the transect, θ_i. Thus, more generally,

$$V = \frac{1}{L}\sum \frac{A_i}{\sin\theta_i} \tag{A2}$$

When log orientation is not known, a weighted mean of potential values can be used instead. The probability that a log will have an intersection with the transect is proportional to sin θ_i and therefore,

$$V = \frac{1}{L}\sum \frac{\int_0^{\pi/2} \frac{A_i}{\sin\theta_i}\sin\theta_i \, d\theta_i}{\int_0^{\pi/2} \sin\theta_i \, d\theta_i} = \frac{1}{L}\sum \frac{\int_0^{\pi/2} A_i \, d\theta_i}{1} = \frac{1}{L}\sum \frac{\pi A_i}{2} = \frac{\pi}{2L}\sum A_i \tag{A3}$$

This can be converted to the standard equation used in inventories based on line-intersect approach (Eq. 1 in the main text) by substituting the equation for the area of a circle, i.e. $\pi(d_i/2)^2$. Note that the use of this equation assumes that cross-sections are circular with no void space – so that it is in fact measuring what we refer to as nominal cross-sectional area, a_i, and nominal volume, V. In reality, $A_i = f_i a_i$, where f_i is a correction factor that accounts for void space and noncircularity.

Mass of woody debris per area (kg/m^2), M, can be calculated by combining information on the true volume with information on the true density (kg/m^3) W_i,

$$M = \frac{\pi}{2L}\sum A_i W_i = \frac{\pi}{2L}\sum f_i a_i W_i \tag{A4}$$

Here, and throughout this appendix, masses are of oven-dried material and wood densities are oven-dry mass per fresh volume (in some publications wood

specific gravity). As explained in the main text, the true density is often difficult to measure but the nominal density, w_i, calculated based on discs of known thickness assuming no void space and circular cross-section, is easily obtained. As $W_i = w_i / f_i$, this offers an alternative way to calculate mass:

$$M = \frac{\pi}{2L} \sum f_i a_i \frac{w_i}{f_i} = \frac{\pi}{2L} \sum a_i w_i \tag{A5}$$

This can be further simplified by introducing cross-sectional mass (kg/m), c_i, defined as the mass (kg), m_i, per unit length (m), l_i, of the piece of wood. Specifically, $c_i = m_i / l_i = a_i w_i$. Thus Eq. A5 simplifies to

$$M = \frac{\pi}{2L} \sum c_i \tag{A6}$$

which is shown as Eq. 2 in the main text. Where orientations are measured, this becomes

$$M = \frac{1}{L} \sum \frac{c_i}{\sin \theta_i} \tag{A7}$$

where θ_i is the angle between the central axis of the ith log and the transect.