PRACTICES AND APPLICATIONS

QUANTIFYING CHAR IN POSTFIRE WOODY DETRITUS INVENTORIES

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ABSTRACT

Charred biomass generated by wildland fire has attracted increased interest as a functional component of terrestrial ecosystems. Black carbon (C) in the form of char is a widespread but unique material contributing to biogeochemical processes including long-term carbon storage and soil productivity. These functions have long been recognized by the biogeochemical and soil sciences, but have so far received little attention from wildland fire science. Fire scientists conducting postfire biomass (or fuel) inventories have an opportunity to quantify the formation of char on woody material, which is important to quantifying interactions between fire and global C dynamics. In addition, failure to account for mass loss due to charring can result in overestimation of down wood biomass and decomposition (12 % to 233 % for particles up to 20 cm diameter). In this paper, we present computational methods that can be incorporated into standard planar intercept transects for estimating black C production and reducing overestimation bias for charred down woody detritus. Methodologies for quantifying black C production in other ecosystem pools are also discussed.

Keywords: black carbon, charcoal, coarse woody debris, fuel consumption, planar intercept transect

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INTRODUCTION

Charred biomass generated by wildland fire (Figure 1) has attracted increased interest as a functional component of terrestrial ecosystems (Forbes *et al*. 2006, Preston and Schmidt 2006, Lehmann 2007, DeLuca and Aplet 2008). Black carbon (C) in the form of char is a unique material contributing to biogeochemical dynamics, particularly to long-

Figure 1. Charred woody detritus, Siskiyou Mountains, Oregon, USA.

term carbon storage and soil productivity (Lehmann 2007, DeLuca and Aplet 2008). Conversion of wood biomass to char by wildland fire can be substantial, in some cases equivalent to the amount that is completely consumed (Tinker and Knight 2000). However, despite growing awareness of its abundance and ecological properties, char has received little attention from the wildland fire sciences, and published field methods for quantifying its formation and functions are scant. Fire scientists conducting postfire biomass (or fuel) inventories have an opportunity to quantify the formation of char on woody material, which may become increasingly important with heightened attention to interactions between fire, C dynamics, and climate (e.g., Schmidt and Noack 2000, Campbell *et al*. 2007).

Quantifying char in postfire biomass inventories, in addition to providing a basic foundation for understanding its ecological function, has the benefit of increasing the accuracy of biomass estimates. Woody material charred but not consumed has lost a large fraction of its mass, commonly estimated at ~70 % loss (Czimczik *et al*. 2002, Dietenberger 2002). If this loss is not taken into account, standard calculations based on field-measured diameters can result in significant overestimation of mass for certain fuel timelag (size) classes.

Ecosystem level estimates of black C formation will require multiple computational approaches addressing various pools (i.e., char on standing wood, down wood, soil). In this paper, we focus on the down woody detritus (WD) pool, presenting computational methods that can be incorporated into standard planar intercept inventories (Brown 1974, Harmon and Sexton 1996) for both estimating black C production and reducing mass overestimation bias associated with charring. Approaches to measuring black C in other ecosystem pools are also discussed.

GENERATION OF CHAR

Char, the thermally altered residue remaining after incomplete combustion of vegetation matter (Baldock and Smernik 2002), is a variable but unique biogeochemical material formed by smoldering and glowing combustion (Goldberg 1985, Pyne *et al*. 1996). Charring results in the loss of labile derivatives of cellulose, hemicellulose, and lignin (e.g., O-alkyl C), leaving biologically recalcitrant compounds including condensed aryl and O-aryl furan structures (Shafizadeh 1968, Pyne *et al*. 1996, Baldock and Smernik 2002, Czimczik *et al*. 2002). The formation of char can be simultaneous with, sequential to, or independent of distillation-based flaming combustion of woody material, with the amount of charring dependent on burning conditions. For example, char formation is likely greatest when and where fuel moisture is high (but below the moisture of extinction), in tightly packed fuels with poor aeration, in material with high lignin:cellulose ratios (greater decay), or under mild burning conditions promoting low-intensity combustion (Pyne *et al*. 1996). Charring affects material to some depth below its surface, depending on moisture and oxygen conditions in a particle's interior, resulting in a blackened rind on the surface of woody detritus (Figures 1 and 2).

GEOCHEMICAL SIGNIFICANCE OF PYROGENIC BLACK CARBON

Char is relatively inert biologically, with long residence times in soils (Goldberg 1985, Baldock and Smernik 2002). This recalcitrance is evidenced by radiocarbon ages of >1000 years (Glaser 1999) and the presence of char C in geological sediments dating to the Devonian period, ~400 million years ago (Schmidt and Noack 2000). Although wildland fires release a pulse of carbon to the atmosphere (Campbell *et al*. 2007), the simultaneous generation of refractory black C suggests that fires also contribute significantly to long-term C sequestration (Schulze *et al*. 1999, Turunen *et al*. 2001, DeLuca and Aplet 2008). Estimates of modern global black C production from biomass burning range from 50 Tg yr^{-1} to 270 Tg yr^{-1} of C (Kuhlbusch and Crutzen 1995), or 1% to 5% of net annual global C uptake by the terrestrial biosphere (see Chapin *et al*. 2002). This process may result in a fire-induced shift of C from the short-term biospheric cycle (fixation and decomposition of organic matter) to the long-term geologic cycle (incorporation into oceanic sediments, subduction, and volcanism), representing a sink for atmospheric C over millennial and

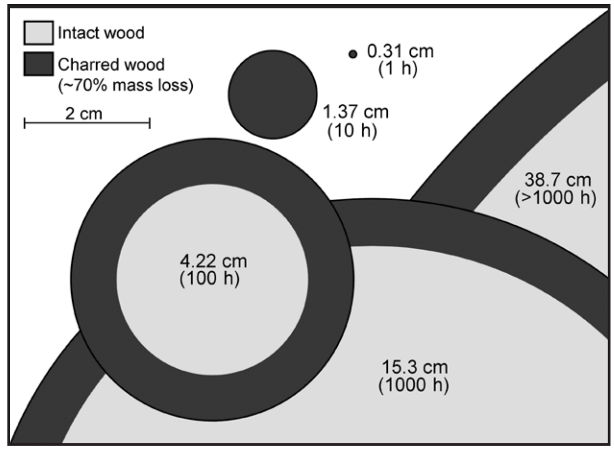

Figure 2. Idealized cross-sectional views of charred woody detritus. Example uses 8.2 mm as typical char depth for downed material, based on field-measured depths. Volume of charred shell relative to overall particle volume is substantial for small particles (e.g., 1 h through smaller 1000 h particles), and relatively unimportant for large particles. Diameters shown are composite quadratic mean diameters for conifer species (see Brown 1974, Harmon and Sexton 1996).

larger time scales (Kuhlbusch and Crutzen 1995). Because C is sequestered in soil char material over the long term, there is interest in its potential to offset increasing atmospheric CO_2 concentrations and there are proposals to include it in emissions trading schemes.

In addition to having long residence times, char has been shown to contribute significantly to long-term soil productivity (Lehmann 2007, DeLuca and Aplet 2008). Char matter adsorbs nutrients in plant-available form (cation exchange capacity) more so than other soil organic matter due to its greater surface area, greater negative surface charge, and greater charge density (Lehmann 2007). The porous structure of char also contributes to lower soil bulk density and higher water retention capacity (DeLuca and Aplet 2008). These properties may sustain soil productivity even under prolonged weathering or agricultural use (e.g., wet tropical environments) (Lehmann *et al*. 2003).

ESTIMATES OF CHAR DEPTH AND MASS LOSS

Although relatively few data exist on typical char mass loss and depth in down woody detritus (WD) under wildland fire conditions, some constraints can be derived from the wood combustion literature. Studies have consistently arrived at estimates of ~60 % to 80 % mass loss on charring for temperatures typical of wildland fires (e.g., Di Blasi *et al*. 2001, Czimczik *et al*. 2002, Dietenberger 2002), with little dependence on heating rate, initial density, burn duration, or wind speed. For char depths, laboratory observations of 0.1 mm to 50 mm have been reported depending on burn times of up to 75 min (Spearpoint and Quintiere 2000). For wildland fires, the limited available data suggest that char depths are fairly consistent and at the low end of this range, with no strong relationship to decay status (sound vs. rotten) (Tinker and Knight 2000).

To provide additional empirical information on char depth, we collected data in three large wildland fires in Oregon: the 2002 Biscuit Fire, 2002 Eyerly Fire, and 2003 B&B Complex Fire. These fires represent a range of forest types including, respectively, mesic Mediterranean Douglas-fir (*Pseudotsuga menziesii*)/sclerophyll, interior ponderosa pine (*Pinus ponderosa*), and high Cascades mixed conifer (Franklin and Dyrness 1973). The data presented here are for illustrative purposes and to provide some likely constraints on char depths under wildland fire conditions, but are not intended to be universal (representative depths should be collected in a given study area; see below). Data were collected during the course of plot surveys 2 yr to 4 yr post-fire (see detailed plot methods below and in Law *et al*. 2008). Because this sampling was exploratory, our objective was to obtain char depths from particles representing a wide range of particle size, species, decay state, and orientation in different forest types. Each WD piece was measured for char depth at three locations around the circumference. The depth to the abrupt boundary between charred and uncharred wood was measured to the nearest millimeter.

Char depths fell within a fairly narrow range (1 mm to 17 mm, mean = 8.2 mm, SD = 3.7 mm, n = 56 pieces) despite variable substrates (sound, rotten, bark, wood, low-intensity surface to active crown fire stands) and different visual appearances of depth. Most notably, char depth did not co-vary with particle diameter (R^2 = 0.09), perhaps because oxygen conditions affecting combustion are similar at a given depth, and this may vary little with overall particle size (J. Agee, University of Washington, personal communication). As such, the proportion of a particle affected by char depended largely on particle size (Figure 2).

COMPUTING BLACK C FORMATION ON WD

We outline here a computational approach designed for easy integration into existing inventory techniques for down WD. By far the most common technique for measuring down wood is the planar intercept method, which allows computation of WD volume and mass using diameter as the only field measurement (Brown 1974, Harmon and Sexton 1996). The planar intercept method carries several major assumptions regarding uniformity of inherently heterogeneous properties such as decay status, particle shape, wood density, etc. (Van Wagner 1982); these have been widely accepted in the biometric literature. Because the approach we present here functions within this framework, it necessarily carries assumptions regarding char similar to those historically used for other characteristics (e.g., uniformity of char around particle circumference, etc.).

The first step in measuring black C formation is to obtain site-specific char depths and their potential relationship to meaningful gradients within the context of study objectives (e.g., forest type, burn severity, etc.). This task requires minimal time and effort, and takes only a blade and a ruler with mm graduations to identify the generally abrupt boundary between charred and uncharred wood. Representative measurements can be taken either as part of normal plot sampling or conducted separately, the latter of which takes less than one field day for a typical fire area. Samples should be taken in a systematic manner (e.g., the first particle tallied on each transect), or stratified-systematic if there are distinctions of interest—e.g., fine vs. coarse WD, bark vs. wood, etc. The appropriate number of measurements taken (*n*) depends in part on whether such distinctions are made but should be >50.

During collection of WD transect data, char can be recorded as a simple presence or absence tally for each piece since there tends to be a relatively narrow range of char depth. Depending on research objectives, a distinction can be made for bark vs. wood char. Like decay status (Brown 1974), the determination of char presence is assessed at the transect line, even if other portions of the particle differ.

Estimates of char depth can then be used to calculate black C mass per area for charred particles, using a straightforward computational approach similar to that described by Tinker and Knight (2000). Standard WD volume calculations (Brown 1974, Harmon and Sexton 1996) are made for the whole particle cylinder including the charred rind, then for an inner uncharred cylinder whose diameter depends on char depth. The difference represents the charred volume. For coarse WD (≥7.63 cm diameter), total volume (Vol_{tot}) is computed using the standard planar intercept scaling equation:

$$Vol_{tot} = 9.869 \times \left(d^2 / 8L\right) \qquad 1$$

where Vol_{tot} is the volume per unit area (m^3 m^{-2}), d is the particle diameter (m), and L is the transect length (m) (Harmon and Sexton 1996). The volume of the core (Vol_{core}) is computed by a similar equation but with a diameter reduction based on char depth:

$$Vol_{core} = 9.869 \times \left(\left[d - \left(2 \times depth_{char}\right)\right]^2 / 8L\right) \qquad 2$$

The difference between these two volumes is the charred volume (Vol_{char}):

$$Vol_{char} = Vol_{tot} - Vol_{core} \qquad 3$$

To obtain black C mass, Vol_{char} is then multiplied by wood density (ρ_{wood}), proportion of mass remaining (0.3), and proportion of final mass that is composed of C (0.75):

$$Black\ C\ mass = Vol_{char} \times \rho_{wood} \times 0.3 \times 0.75 \qquad 4$$

assuming 70 % mass loss and 0.75 final C mass fraction with heating to 300 °C to 400 °C (Baldock and Smernik 2002, Czimczik *et al*. 2002, Branca and Di Blasi 2003).

For fine WD, charred 1 h timelag (0 cm to 0.62 cm) and 10 h timelag (0.63 cm to 2.54 cm) particles may be presumed to be all char (Figure 2). Thus, biomass per area of these classes (obtained by standard computations; Brown 1974, Harmon and Sexton 1996) can be multiplied by (0.3) to obtain a char-corrected mass, and by 0.75 to obtain black C mass. The 100 h timelag (2.55 cm to 7.62 cm) particles are large enough that they likely have an uncharred core (Figure 2); thus they would be treated in similar fashion to coarse WD, using the quadratic mean diameter for that size class.

In simplified terms, the amount of black C generated per length of WD particle scales linearly with particle size, because the size of the charred rind depends largely on circumference (linear function ~ 2πr) (Figure 3). Coarse WD is therefore typically the main contributor of black C at stand and larger scales.

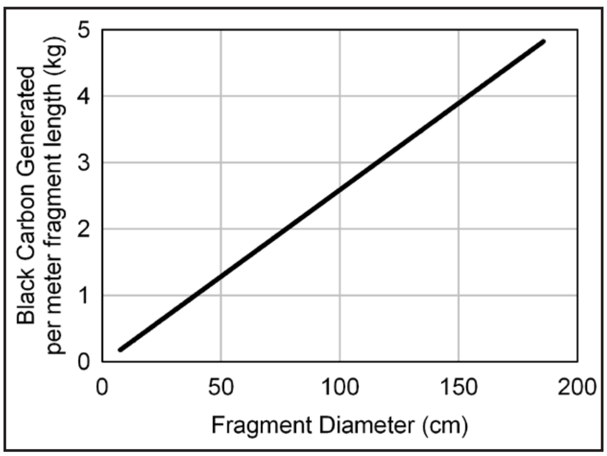

Figure 3. Black carbon generated by wood charring, per meter of particle length, assuming uniform char depth around particle. Amount scales linearly to diameter because size of charred rind depends on circumference of particle (linear function ~ 2πr).

OVERESTIMATION BIAS FOR CHARRED WD MASS

Sampling error aside, the planar intercept method effectively accounts for the portion of WD completely consumed by fire because the reduced diameters should be reflected in the measurements. However, the technique does not account for material charred and remaining as a rind on WD (Figure 2). Calculations of WD mass based on field-measured diameters assume the density of char layers to be unaltered, when in reality they have lost much of their mass (Di Blasi *et al*. 2001, Czimczik *et al*. 2002, Dietenberger 2002). This bias can result in substantial overestimation of postfire WD mass for all but the largest timelag classes.

Literature estimates of mass loss on charring (~70 %) and field-measured constraints on char depth (typically <15 mm, mean 8.2 mm) allow an assessment of overestimation bias for WD inventories. Applying the inner-core outer-shell method adapted from Tinker and Knight (2000), total particle mass ($mass_{corr}$) is obtained by multiplying the volume of the uncharred core (Vol_{core}) by wood density (ρ_{wood}), then adding the volume of the charred exterior (Vol_{char}) multiplied by wood density with 70 % mass loss:

$$TotalParticleMass(mass_{corr}) = Vol_{core} \times \rho_{wood} + Vol_{char} \times \rho_{wood} \times 0.3 \quad (5)$$

This corrected mass can be compared to standard mass computations, which are based on conversion of whole-particle volume to mass using a single wood density value ($mass_{uncorr}$). Percent overestimation bias is calculated as the difference between the uncorrected mass estimate ($mass_{uncorr}$) and the corrected mass estimate ($mass_{corr}$) divided by the corrected estimate and scaled to percentage:

$$OverestimationBias = 100 \times \left(mass_{uncorr} - mass_{corr}\right) / \ mass_{corr} \quad 6$$

Overestimation is substantial for smaller size classes, rapidly tapering off with particle diameter (Table 1, Figure 4). The bias is non-trivial for all but the largest size classes. For example, if char rind is not accounted for, 1 h and 10 h timelag particles are overestimated

Table 1. Potential overestimation bias for charred woody detritus (WD) particles by size class.

	Timelag class[1] (h)	Quadratic mean diameter[2] (cm)	Fractional mass loss due to charring	Over-estimation of mass (%) (Equation 2)
Fine WD	1	0.31	0.70	233
	10	1.37	0.70	233
	100	4.22	0.47	89
Coarse WD	1000	15.3	0.14	17
	>1000	38.7	0.06	6.2

[1] 1 h, 0 cm to 0.62 cm diameter; 10 h, 0.63 cm to 2.54 cm; 100 h, 2.55 cm to 7.62 cm; 1000 h, 7.63 cm to 20.32 cm; >1000 h, >20.32 cm.
[2] Quadratic mean diameters are composite conifer values (see Brown 1974, Harmon and Sexton 1996).

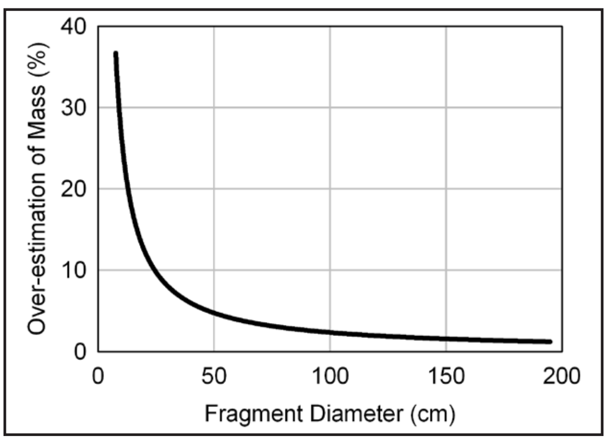

Figure 4. Estimated positive bias in WD mass computations, expressed on a percentage basis, when wood charring is present but not taken into account. In this example, empirically-derived values of char depth (8.2 mm), mass loss on charring (70 %), and consistency of char depth across particle sizes are used (see text). Shape of curve reflects the relationship between total cross-sectional area, which varies with the square of particle radius (πr^2), and a rind of fixed width, which increases linearly with radius ($2\pi r$).

by more than a factor of 3 (233 %), 100 h particles by 89 %, and even 1000 h (7.63 cm to 20.32 cm) particles by 12 % to 37 %, depending on exact size (Table 1, Figure 4). Charred 1 h particles may be of lower relevance to WD inventories because they could be missed, or dismissed, as litter rather than wood. Also, for the largest particles (>50 cm), the bias of less than 5 % is relatively unimportant for mass estimates; the error associated with thick bark may well surpass that associated with char. However, these pieces generate the most black C per particle length (Figure 3).

CORRECTING MASS ESTIMATES FOR CHARRED WD

Woody detritus mass estimates typically have low precision for all but the most intensive sampling efforts (Harmon and Sexton 1996) due to several sources of uncertainty including sampling error, variations around quadratic mean diameters, irregular particle shapes, bark presence and looseness, decay class categorization, etc. Nevertheless, correcting for mass loss on charring can still increase accuracy because the error in not doing so is unidirectional (systematic positive bias). Doing so is primarily important for fine WD and smaller particles of coarse WD, whereas for large particles or total WD inventories (which are dominated by large particles), it likely makes little difference.

A simple computational adjustment incorporates mass loss for charred particles. The method arrives at the same adjustment as the inner-core outer-shell method used by Tinker and Knight (2000) and for the bias estimates above, but differs in that it can be easily routed through standard equations for volume and mass per unit area. The standard equation for scaling coarse WD particle diameters to volume per unit area (Equation 1) would still be applied to all uncharred particles. For charred particles, *d* can be substituted with an adjusted "pseudo-diameter" (d_{adj}) based on the depth of char. This value is equivalent to the diameter of the entire particle minus 70 % of the charred rind:

$$d_{adj} = d - (2 \times depth_{char} \times 0.7) \qquad 7$$

where $depth_{char}$ is in the same units as d. Practically, this adjustment collapses the 30 % remaining mass in the charred rind into a narrower outer ring (with 30 % of the volume of the charred rind). Equation 7 also incorporates a factor of two (similar to Equation 2) because the equation is based on diameter rather than radius, and a 70 % mass reduction based on literature values for mass loss on charring (Czimczik *et al*. 2002). An adjusted volume equation results:

$$Vol_{adj} = 9.869 \times \sum \left([d - (2 \times depth_{char} \times 0.7)]^2 / 8L \right) \qquad 8$$

from which mass is calculated with standard wood densities. This adjustment can also be applied to the quadratic mean diameters used for fine WD calculations (Harmon and Sexton 1996), with the recognition that the smallest classes (1 h and 10 h) are likely charred to the core, in which case a simple mass reduction of 70 % can be applied.

These calculations assume approximately uniform charring over the length and circumference of a WD particle. There is likely substantial variation under field conditions. This variation is mostly an issue for large particles with greater surface area, while smaller particles tend to char rather uniformly. Tinker and Knight (2000) noted that most WD was either nearly completely charred or not charred at all following wildland fire, which is consistent with our observations. Such assumptions are essentially identical to longstanding (and imperfect) assumptions regarding decay state, particle shape, wood density, etc. (Van Wagner 1982), and are what make the approach easily incorporated into existing techniques. Another consideration is that the above calculations presume consistent char depth in wood regardless of particle diameter, based on our field measurements. If field measurements in a given study area suggest that this varies, the equations here could be easily amended to reflect this variability (e.g., with a function rather than a fixed depth).

EMPIRICAL EXAMPLE OF POSTFIRE WD INVENTORY

For illustration, we applied the above computations to an actual postfire WD inventory, using data from 50 plots in stand-replacement portions of the 2002 Biscuit Fire (Table 2). Twenty-five plots were in areas burned once in the Biscuit Fire, and 25 were in areas where the Biscuit Fire re-burned stand-replacement portions of the 1987 Silver Fire. We conducted the field survey two years after fire, surveying 300 m of transect line within each plot (four 75 m transects in subcardinal directions). Coarse WD (1000 h and >1000 h classes) was surveyed along all 75 m of each transect, while fine WD survey lengths were, beginning from the distal end of transects: 1 h, 5 m; 10 h, 15 m; 100 h, 25 m.

Applying the equations outlined above, summed across all size classes, black C generation (on down wood only) in areas experiencing one high-severity fire was estimated to be ~300 kg ha^{-1}. Large particles, by far, accounted for most black C formation, while fine WD contributed relatively little (Table 2). With respect to overestimation bias, not all WD particles in a stand were charred and bias estimates were therefore much lower than the theoretical maxima. However, overestimation of mass by not accounting for char was still significant, ranging from 6 % to 19 % for 1 h through 1000 h particles (Table 2). Bias was effectively negligible for large (>1000 h) particles (Table 2).

Table 2. Empirical example of over-estimation bias and black C formation from down wood inventory, using data from stand-replacement portions of the 2002 Biscuit Fire, Oregon. Portions of the Biscuit Fire re-burned an area that had burned 15 years prior, in the 1987 Silver Fire.

Burn history	Timelag class (h)	Un-corrected mass (kg ha^{-1})	Char-corrected mass (kg ha^{-1})	Over-estimation bias (%)	Black C formation (kg ha^{-1})
Single stand-replacing fire [*n* = 25 plots]	1	261	246	5.9	4.6
	10	681	598	13.9	26.7
	100	1 170	982	19.2	64.7
	1000	2 074	1 947	6.5	40.0
	>1000	29 613	29 100	1.8	164.0
Two successive stand-replacing fires [*n* = 25 plots]	1	109	89.2	22.0	6.3
	10	786	608	29.2	57.0
	100	2 789	2 353	18.6	150.0
	1000	6 356	5 721	11.1	200.2
	>1000	23 589	22 831	3.3	241.7

In re-burned stands, more exposed surface area of decayed wood (from standing and down trees killed in the first fire) had the potential to increase charring levels. Certain size classes of WD were more prevalent in the reburn (e.g., 100 h and 1000 h), and those present were likely to have shed bark and decayed significantly, two factors increasing the likelihood of wood charring. Indeed, black C generation and overestimation biases (11 % to 29 % for 1 h through 1000 h) were consistently higher in these stands (Table 2). Summed across all size classes, black C generation in the re-burn area (on down wood only) was estimated to be ~655 kg ha^{-1}—over twice that of single-burn stands.

CONTEXTUAL RELEVANCE OF CHAR ON WD

Quantifying char may be most relevant when generation of black C is of interest and when precise estimates of WD are needed by size class. Quantifying char may be unimportant when WD will only be reported by volume, or when mass will only be reported with a single number for total amount (a number governed mainly by large particles for which overestimation bias is minimal).

Other potential implications of char merit further research. Possibilities include influence of the fractured and fissured nature of charred material when estimating volume, examination of the presence or absence of bark and how it influences charring and wood density, influence on decay rates, habitat suitability for WD-dependent organisms, and fuel properties affecting availability for subsequent fires.

OTHER ECOSYSTEM BLACK C POOLS

The primary focus of this paper is to highlight the importance of pyrogenic black C, and to make an easily integrated method available for quantifying its formation on one important ecosystem pool, down woody detritus. Assessing total ecosystem black C following fire would require also measuring char on standing trees (live and dead) as well as in and on the soil. These pools will likely require separate sampling strategies and further methodological refinement. For example, widely accepted efficient methods for quantifying black C in soil have not been developed, even by geochemists who focus on these dynamics (see DeLuca and Aplet 2008). General issues and approaches for these other pools are discussed here.

For standing trees, char usually affects the bole from the base up to some height depending on fire behavior (flame length, energy release, surface vs. crown fire, etc.). Thus, measurements of both char depth and char height would likely be needed. One possible method is to obtain representative char depths on standing material (using similar subsampling approach to that for down wood), then record char heights for each tree measured in plot surveys, with the diameter taken near the base (e.g., dbh) and estimated at the top of the scorched section. From these numbers, the surface area of a conical frustum can be calculated, and black C computed similarly as for WD:

$$Black\,C\,mass\,(tree) = \left[\pi \times (r_1 + r_2) \times \sqrt{\left((r_1 - r_2)^2 + h^2\right)}\right] \times depth_{char} \times \rho_{wood/bark} \times 0.3 \times 0.75 \qquad 9$$

where the terms in brackets constitute the surface area of the scorched frustum, while the remaining terms convert this surface area to volume and mass, then adjust for mass loss on charring and final C concentration. (Note that a similar frustum technique could also be applied to down material for protocols in which WD volume is calculated from measurements of piece lengths and end-diameters (e.g., Law *et al*. 2001, Waddell 2002). Live or recently killed trees will primarily have bark charring, while pre-existing snags may have any combination of bark and wood charring. As with down WD, it may be of interest or quantitative importance to distinguish between bark and wood charring on standing trees and snags (e.g., ρ_{bark} would be used in place of ρ_{wood}; see Equation 9). One consideration for this approach is the occurrence of asymmetry in vertical scorch, wherein charring is much higher on one side of a bole than the other; this would require more complex geometric approximations than a simple frustum.

A large fraction of ecosystem black C exists on or in the soil (DeLuca and Aplet 2008). Recently fire-generated black C lies partly on the soil surface, resulting from incomplete combustion of surface organic layers (litter and duff). Because this material is patchily distributed, quantification of this pool may require collection and weighing of material from sampling frames (e.g., 0.25 m^2 rectangle or ring), located systematically or randomly within survey plots. Several samples (i.e., ≥12) would need to be taken at each survey plot to account for spatial variation. Finally, belowground black C generated by smoldering of roots may be the most difficult pool to evaluate, requiring soil excavation or extensive coring effort, followed by isolation of black C from the soil matrix, and weighing. The relative contribution of this pool versus others in the generation of total black C is likely significant, but has not been well quantified.

SUMMARY OF COMPUTING AND REPORTING CHARRED DOWN WD

Several steps are necessary to compute and report charred down woody detritus. First one must obtain a representative sample of char depths for a given study area. Appropriate sample size depends on any distinctions of interest (e.g., fine vs. coarse WD, bark vs. wood, fire severity, etc.), but should be >50. Next, the presence or absence of char for each WD particle encountered during surveys must be recorded. Then, if it is a research objective, it is necessary to calculate black C formation by Equation 4. Finally, to reduce overestimation associated with charring, diameters must be adjusted to reflect char effects, and then mass should be calculated in the normal manner. This correction is primarily important when reporting WD mass by size class.

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