Separating Duff and Litter for Improved Mass and Carbon Estimates

David Chojnacky, Michael Amacher, and Michael Gavazzi

ABSTRACT

Mass and carbon load estimates, such as those from forest soil organic matter (duff and litter), inform forestry decisions. The US Forest Inventory and Analysis (FIA) Program systematically collects data nationwide: a down woody material protocol specifies discrete duff and litter depth measurements, and a soils protocol specifies mass and carbon of duff and litter combined. Sampling duff and litter separately via the soils protocol would increase accuracy of subsequent bulk density calculations and mass and carbon estimates that use them. At 57 locations in North Carolina, Virginia, and West Virginia, we measured depth, mass, and carbon of duff and litter separately. Duff depth divided by total depth varied from 20% to 56%, duff was 1–4 times denser than litter, and the calculated median carbon-to-mass ratio for hardwood duff (0.37) was less than that for litter (0.45). Using FIA depth measurements, we calculated mass from (1) our mean density values, (2) a mass versus depth regression model we developed, and (3) published density values. Model mass calculations were lower than those using our mean densities, possibly because the latter ignore density differences with layer thickness. Our model could provide valuable mass and carbon estimates if fully developed with future FIA data (duff and litter separated).

Keywords: organic soil horizon, down woody materials, soil survey

The Forest Inventory and Analysis (FIA) program of the US Forest Service offers the largest source of forest data in the United States. In this study, we investigated the efficacy of a potential improvement to an FIA protocol, a small change that could yield a wealth of data for researchers who want to address regional and national management issues, for example, diversity among US forest types or continental-scale carbon sequestration.

Forests and forest soils are vital components of the global carbon cycle. Increased carbon dioxide emissions have resulted in increasing concern about global climate change. Understanding of forest processes, particularly with regard to carbon cycling, and protection of forest health have assumed greater prominence in national and international policy development. Understanding depends on good data. For example, foresters need to be able to estimate mass and carbon load of forest components as accurately as possible.

Forest managers commonly sort forest floor components or down woody materials into successive layers: understory shrubs and herbs, branches and logs (fine and coarse woody material), litter, and duff. Literature definitions of duff and litter vary; in this article, we follow the Forest Service (e.g., FIA 2005a) definitions. Duff includes the dark, partly decomposed organic material (unrecognizable plant forms) above mineral soil. Litter, on top of duff, includes recognizable plant parts, such as leaves and flowers, but not branches (twigs 6 mm in diameter or larger) (Figure 1).

The organic duff and litter layers play critical physical, chemical, and microbiological roles in forest ecosystems (Graham et al. 1999). Duff contains many ectomycorrhizal fungi that have symbiotic relationships with tree and shrub roots; these partnerships aid in the uptake of water and certain nutrients and may protect the surrounding soil structure and protect against other soil-borne organisms (Fitter and Garbaye 1994, Smith et al. 2005). Duff and litter protect the soil from erosion and compaction and form a mulch for maintaining soil moisture (Bonan 2002). The forest floor is critical for nutrient cycling (Sanchez et al. 2006), and many nutrients—including nitrogen, phosphorus, calcium, magnesium, and potassium—are stored for release during decay or burning of duff and litter (Switzer et al. 1979).

Duff and litter are also important for carbon sequestration. Heath et al. (2003) report for US forests that 50% of total carbon is in the soil and another 8% is on the forest floor; duff and litter (by our definitions) are components of the soil and the forest floor. Page-Dumroese and Jurgensen (2006) measured forest floor and soil carbon in the same range generally reported for aboveground forest carbon. Chojnacky and Amacher (2006) also previously calculated that about half of forest carbon was in the soil and forest floor, although those calculations were rough estimates.

The FIA program conducts annual surveys of all forestland in the country by using a systematic, statistically sound design of rotating panels, where 120,000 plots are remeasured on 5–10-year cycles (FIA 2007a). This expansive sampling provides forest data on a scale that cannot be matched by typical research programs. The FIA design includes three phases to monitor field plots across all land

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Received July 26, 2007; accepted January 7, 2009.

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.039 in; square centimeters (cm^2): 1 cm^2 = 0.155 $in.^2$; millimeter (mm): 1 mm = 0.039 in.

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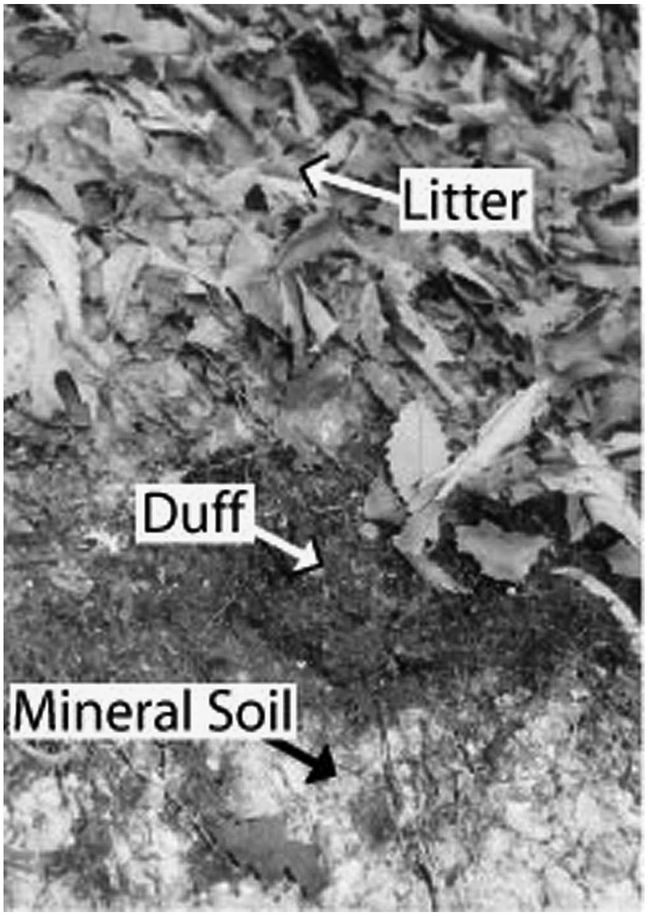

Figure 1. Forest floor litter and duff layers above mineral soil (Shenandoah National Park, VA).

ownerships (Bechtold and Patterson 2005): a phase 1 (P1) consisting of remote-sensing coverage to determine forest area; a phase 2 (P2) grid of field plots to measure trees; and a phase 3 (P3) subsample of P2 field plots to collect more detailed forest health information, including duff and litter measurements.

FIA uses two different sampling protocols to collect information about duff and litter in P3 sampling. A down woody materials (DWM) protocol (FIA 2005a) includes simple, discrete depth measurements of duff layers and litter layers along transects; a soils protocol (FIA 2005b, O'Neill et al. 2005) includes discrete depth measurements and samples of combined duff and litter material ("organic forest floor") for laboratory measurement of mass and carbon. The mass (*M*) and volume (*V*, equal to area times depth) of the combined samples are used to calculate density (*D*) of the organic forest floor for various forest types ($D = M/V$; Ophart 2003). Currently the DWM and soils protocols are implemented for about 1/16th of FIA's P2 plots; however, some form of the DWM procedure is being considered for wider application, to provide duff and litter depth measurements for all FIA P2 plots.

Currently, where mass and carbon are not directly measured, forest managers use discrete duff and litter depth measurements and published density values for various forest types to calculate mass and carbon at their sample site. This method is easy to apply because only depth needs to be measured in the field. The mass calculation assumes a uniform density of the volume for a 1-cm^2 area around the depth measurement.

This mass calculation presents a difficulty because the densities of duff and litter needed are not available for all forest types. Woodall and Williams (2005) listed known duff and litter density values for North American species, but these were primarily limited to western forest types and to individual tree species (values difficult to use with mixed-species forest types). Woodall and Monleon (2008) provide density values for FIA forest type groups but note they are subject to revision and recommend using local or regional values when available. The FIA soils protocol offers a potential opportunity to fill in the missing density values because organic forest floor (duff plus litter) samples of measured volume are brought back to the laboratory for mass determination. Theoretically, densities of duff and litter could be calculated for every FIA forest type in the country as P3 data become available from the 1/16th subsamples.

However, because FIA combines duff and litter during the field sample collection, there is no opportunity to calculate separate duff and litter densities. A combined duff and litter density has limited value because duff is generally more than twice the density of litter (Woodall and Williams 2005), in contrast to the assumption of uniform density discussed above.

This study was initiated to investigate the efficacy of collecting separate duff and litter samples—by following the FIA soils protocol but sorting duff from litter in the field. The expectation was that such separated data would be easy to collect and would provide more accurate duff and litter bulk density values for use in calculating mass and carbon.

Methods

Site Descriptions

Data were collected at 57 locations in northern North Carolina, Virginia, and West Virginia. In August 2005, the Virginia and West Virginia sample sites were selected near roads (for convenience), across a range of elevations from 2 to 440 m (7 to 1,444 ft) in the George Washington Memorial Parkway, George Washington National Forest, and Monongahela National Forest. In September

Table 1. Duff and litter samples from 57 locations in North Carolina, Virginia, and West Virginia, from near sea level to 440-m (1,444-ft) elevations, on forested lands in a national park, in two national forests, and on private timber company property.

	Predominant tree species							
	Hardwood		Oak		Conifer		Pine	
Sampling location	Plots (no.)	Mean elev. (m)	Plots (no.)	Mean elev. (m)	Plots (no.)	Mean elev. (m)	Plots (no.)	Mean elev. (m)
George Washington Memorial Parkway, VA	7	14	3	22				
George Washington National Forest, VA/WV	5	167	12	177	1	93	1	93
Monongahela National Forest, WV	12	292	2	125	3	440	1	372
Weyerhaeuser Co., Washington County, NC							10	2
Total	24	185	17	143	4	353	12	40

Figure 2. Litter and duff layers collected separately within a 30.5-cm-diameter bicycle tire and bagged in plastic for transporting to laboratory (Monongahela National Forest, WV). For each litter and duff sample, four depth measurements were made (at the ends of four ribbons at 90° angles approximately 6 cm from the inside of the tire).

2005, we sampled a 13-year-old loblolly pine (*Pinus taeda*) plantation on Weyerhaeuser lands in Washington County, North Carolina (Table 1). Samples were collected from representative forest conditions at each of the locations.

We sampled a variety of forest species mixtures across the elevation gradient at points where both duff and litter were present. Data collection, which was resource-limited, was not designed to statistically sample a given population area; rather, the goal was only to obtain sufficient samples to enable further study of individual duff and litter properties, so that protocol refinement recommendations could be made to FIA.

Sample Collection

At each sample location, the FIA soils protocol (FIA 2005b) was used to collect material within a 30.5-cm (12-in.) bicycle tire (a convenient, lightweight plot "sampling frame") that was tossed to the ground in the representative area chosen. Layer depth was measured to the nearest 1–2 mm (0.04–0.08 in.) by using a steel caliper with a moving crossbar that could be adjusted to match the depth and then held up to the eye for careful reading. Four litter-depth measurements (to the nearest 2 mm or 0.08 in.) were taken at 90 degrees from each other about 6 cm (2.4 in.) in from the inside of the bike tire (Figure 2). Then litter was carefully collected into plastic zipper storage bags. Duff depth was similarly measured to mineral soil, and then duff was collected.

A small saw often was used to cut around the circumference of the sample before removing material to avoid pulling in material from outside the tire. Pieces of fine woody material (6 mm in diameter and larger), bark, cones, and rocks were removed and discarded, but shrub and tree roots were kept. In George Washington Memorial Parkway, boundaries between layers were difficult to discern because of excessive disturbance from exotic earthworms (Gundale 2002). Also collected at each sample site was a listing of predominant tree species in the area. No other tree measurements were made.

Laboratory Analyses

Bagged samples were kept at room temperature and mailed within 1 week to the Forest Service soils laboratory in Logan, UT. Field-moist, air-dried, and oven-dried sample weights and water contents of the duff and litter samples were measured using current FIA soil analysis protocols (Amacher et al. 2003). The air-dried samples were ground in a Wiley mill to <10-mesh; a 100-mg subsample of each air-dried and ground sample was analyzed for total carbon. Carbon was determined by combustion at 950°C in a LECO TruSpec Carbon and Nitrogen Analyzer (LECO Corporation, St. Joseph, MI) calibrated with EDTA (ethylene diamine tetra-acetic acid). Instrument calibration and performance were verified with repeat analysis of standard reference materials of known carbon contents.

Results and Discussion

Prior to analyses, data were examined graphically for relationships and errors. We observed some trends associated with tree species when plotting mass data against depth data. Unfortunately, the species data had not been collected for precise grouping, but we were able to assemble four species groups based on our field notes of trees in the area: oaks, all other hardwoods, pine (mostly in plantations), and all other conifers.

Also after graphical examination, we deleted three duff and two litter samples with less than 5 g (0.18 oz.) mass or less than 1 mm (0.04 in.) depth. These small amounts of material appeared inconsistent with the rest of the data for volume or density calculations. Duff from four additional sites (in George Washington Memorial Parkway) was nonexistent because excessive exotic earthworm activity had consumed or mixed it with mineral soil. The final count was 50 duff samples (57 minus 3 deleted and 4 that were zero), 55 litter samples (57 minus 2 deleted), and 57 combined duff and litter samples for analysis.

Ease of Collection

We found it straightforward to separate duff from litter in the field on the basis of FIA definitions unless earthworms or other disturbance mixed the two layers. There were judgment calls near boundaries, but the layering of material followed a natural time sequence where decomposition (and thus density) gradually changed from top to bottom. Classification of soil horizons is well established, and although there is some margin of error involved, accepted FIA practice already includes measuring depths of separate duff and litter layers.

If FIA field procedures shift toward collecting duff and litter separately, it will be necessary to consider situations where separate collection is impractical or impossible. For example, our study recorded some average layer-depth measurements less than 1 cm (0.4 in.) (particularly for duff) and a few even less than 1 mm (0.04 in.). These average depths were the mean of the four measurements within the sample frame, where some equaled zero; perhaps four depth measurements are too few within a 30.5-cm sampling frame, particularly when material is distributed in clumps. The small depths seemed to cause problems in the bulk density calculation because of inaccurate volume calculation, where the small sample depths (of several mm) could easily have measurement error of 100–200%. Such error might be overcome with more depth measurements for shallow layers, but a minimum depth is probably needed below which separation of duff from litter should not be attempted; in such cases duff should be combined with litter.

We did not collect enough data to make sound recommendations on a minimum depth, but such a protocol could probably be

Table 2. Bulk density of litter and duff for 57 samples collected in North Carolina, Virginia, and West Virginia.

		Bulk density				
		Mean				
Species group	Layer	g/cm^3	lbs/ft^3	Median (g/cm^3)	CI[a] (%)	Samples (no.)
Oak	Litter	0.03	1.89	0.03	20	17
	Duff	0.11	6.87	0.10	24	17
	Combined	0.05	3.43	0.05	16	17
Hardwood	Litter	0.02	1.44	0.02	18	22
	Duff	0.09	5.36	0.09	19	18
	Combined	0.04	2.36	0.03	26	24
Pine	Litter	0.03	1.78	0.03	19	12
	Duff	0.06	3.90	0.06	23	11
	Combined	0.04	2.30	0.03	21	12
Conifer	Litter	0.09	5.36	0.08	51	4
	Duff	0.11	6.58	0.11	56	4
	Combined	0.09	5.75	0.10	37	4
Total	Litter	0.03	1.94	0.03	17	55
	Duff	0.09	5.65	0.08	13	50
	Combined	0.05	2.90	0.04	14	57

[a] 95% confidence interval, expressed as percentage of mean density.

established if additional depth measurements (eight or more total) were taken when a mean layer depth within a sample frame was less than 10 or 15 mm (0.4 or 0.6 in.). After one or two field seasons, such data could be analyzed for making recommendations about when to take additional depth measurements and how many are needed. Such data would also illustrate where additional depth measurements are of little value below a certain threshold depth and provide guidelines on the ramifications of combining duff with litter for a variety of situations where either duff or litter depth was minimal.

In addition, more study could be given to an appropriate measurement device for layer depths. Perhaps instruments more precise than our steel caliper with moving crossbar could be found or devised.

Bulk Density Calculation

Mean bulk density was calculated from mass and volume for the four species groups and in total, for duff and litter separately and combined (Table 2). The closeness of mean and median bulk density suggests that outliers did not skew data.

For oaks and other hardwoods, the density of duff was 3–4 times the density of litter. For pine and other conifers, duff density was closer to litter density, at only 1–2 times larger, possibly because needles seem to form litter that is more compact. However, the high conifer litter values reflect mostly red spruce (*Picea rubens*) samples, and the small sample size precludes strong inference from these data for all conifer species.

The percentage of duff depth to total depth varied considerably. The average percentages of duff-to-total depth were 31%, 20%, 24%, and 56% for oak, hardwood, pine, and conifer, respectively.

The consistently larger density of duff over litter and the variation in proportion of duff illustrate the importance of separating the two for use in calculating mass from depth measurements. For example, although Table 2 shows combined duff and litter densities, these are not recommended for use with combined duff and litter depth measurements because they would be applicable only to situations where proportions of duff match our data.

Carbon Conversion

We developed methods for converting duff and litter mass to carbon for use in addressing greenhouse gas issues, carbon sequestration, and other management needs. We collapsed species groups into conifer and hardwood because these were the only categories that could be distinguished when plotting carbon against mass data; for litter, even this distinction was minimal.

Carbon-to-mass ratios were averaged within the conifer and hardwood groups for litter and duff, separately and combined (Table 3). These data were normally distributed except for a lower tail of a few small values, which influenced the means. Note that the 5th percentiles in the table are much farther from the median than are the 95th percentiles. Therefore, the median seemed more appropriate than the mean for the carbon-to-mass ratio factor.

Further analysis supported the median as the most reasonable estimate to use for converting mass to carbon. A regression analysis was conducted where carbon-to-mass ratio was defined as the slope of carbon regressed against mass with no intercept included. Results were identical to the median except for hardwood duff, which included one large mass observation with low carbon (0.2 carbon-to-mass ratio) that highly influenced the regression.

Carbon content of mass can be quite different for duff and litter, reinforcing the value of separating duff from litter in collection, processing, and analysis. Our litter conversion factors were near the 50% commonly used (Heath et al. 2003) for live tree wood and foliage, but our duff factor for hardwood was considerably less than 50% and closer to one-third (Table 3).

Regression of Mass versus Depth

Instead of using bulk density to calculate mass of duff and litter from depth measurements, mass can be modeled directly as a function of depth, as suggested by Stephens and Finney (2002) for some California forests. If duff and litter are measured separately, it is reasonable to assume uniform density over the discrete duff and litter depth measurements, and following the basic density formula discussed above ($M = D \cdot 1\ \text{cm}^2 \cdot \text{depth}$), mass is proportional to depth.

Although our graphical analysis showed a strong linear relationship between mass and depth for duff and litter, simple linear regression was not used because a positive or negative intercept would have resulted in illogical model predictions for small near-zero depth measurements for most species groups. We considered regression with no intercept (constrained to pass through the origin) but found that a natural log transformation of the data, which also eliminates an intercept, allowed more flexibility. Nonlinear regression also was considered but dismissed because preliminary results were similar to those of the log transformation, indicating no need for additional complexity.

One model was fit for duff and litter each, and species groups were accounted for by using dummy variables. Because our data represented only a small sample and were not intended for definitive model construction, we stopped when we achieved reasonable-looking log models.

The model fit the data with reasonable precision, as shown by R^2 values (coefficient of determination in log units) of 0.75 and 0.66 for duff and litter, respectively (Table 4). An optional log transformation or bias correction factor is given in Table 4 because logarithmic regression (using log transformation) theoretically estimates a median instead of a desired mean (Flewelling and Pienaar 1981). For our modeling, the bias corrections were 1.07 for duff and 1.05

Table 3. Carbon-to-mass ratio for converting duff and litter mass to carbon.

		Carbon-to-mass ratio					
Species group	Layer	Mean	CI[a]	5th Percentile	Median	95th Percentile	Samples
Conifer	Litter	0.46	4	0.36	0.47	0.49	16
	Duff	0.42	11	0.15	0.46	0.48	16
	Combined	0.45	5	0.34	0.47	0.48	16
Hardwood	Litter	0.44	4	0.35	0.45	0.49	41
	Duff	0.36	9	0.19	0.37	0.48	37
	Combined	0.40	5	0.28	0.42	0.47	41

[a] 95% confidence interval, expressed as percentage of mean carbon-to-mass ratio.

Table 4. Model and parameter estimates for duff and litter mass prediction.

	Parameters							
Model	β_0	β_1	β_2	β_3	β_4	MSE	R^2	*n*
Duff	2.0388	0.7474	0.3113	0.3083	−0.2076	0.1427	0.75	50
Litter	1.0533	0.6280	0.3145	1.0200	0.4112	0.0906	0.66	55

$Y = \text{Exp}\ (\beta_0 + \beta_1 \text{ In depth} + \beta_2\text{O} + \beta_3\text{C} + \beta_4\text{P})\ \theta$, where Y = duff or litter mass (Mg/ha) (for ton/acre multiply by 0.446 depth = material depth [cm]); O = 1 if forest equal oak species, 0 otherwise; C = 1 if forest equal conifer species (except pine), 0 otherwise; P = 1 if forest equal pine species, 0 otherwise; $\theta = \text{Exp(MSE/2)}$ (optional log transformation correction factor).

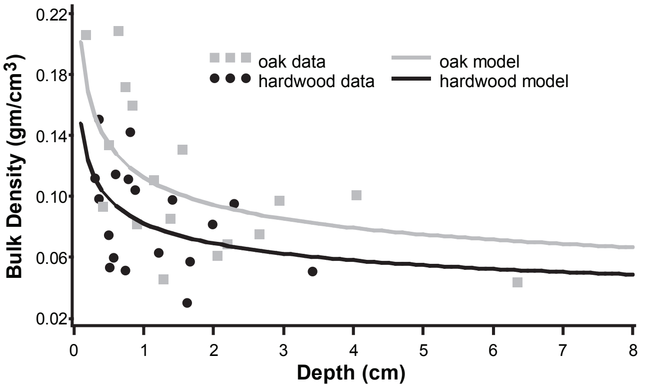

Figure 3. Oak and hardwood duff bulk density calculated from mass model prediction (*D* = *M*/*V*, where *V* = depth by assuming 1-cm² area around depth) overlaid on duff densities calculated from measured mass, area, and depth.

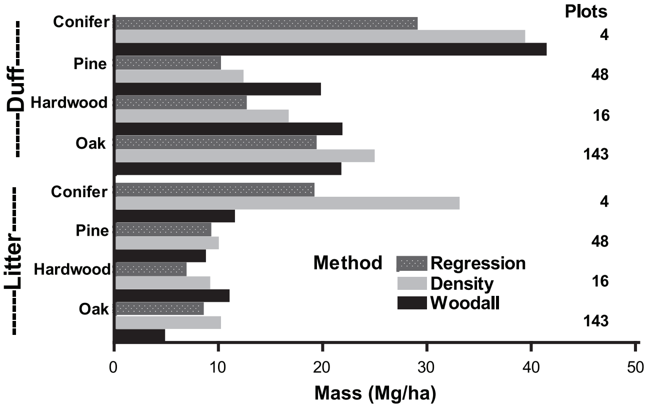

Figure 4. Comparison of duff and litter mass calculations using (1) mean bulk density values calculated from discrete duff and litter samples in this study, (2) regression model of mass versus depth, and (3) published density values (Woodall and Williams 2005). Calculations used depth measurements from the publicly available data for 211 FIA plots measured across North Carolina, Virginia, and West Virginia (FIA 2007b).

for litter, which translate to 7% and 5% increase in mass predictions, respectively. We include the bias correction for completeness, but users may decide whether to use it.

When our regression predictions were converted from mass to density, and the model curves plotted with the bulk density data calculated directly from mass and volume measurements, the curves illustrated the decreasing trend in density as depth increased for oak and hardwood species groups (Figure 3). There were fewer pine observations, which did not necessarily support or refute this trend.

Method Comparison

We compared mass calculations using published FIA depth measurements with (1) our mean bulk density calculations, (2) our regression model, and (3) published density values (Woodall and Williams 2005). The latter were the best available for use with FIA data at the time of our study.

Calculations used depth measurements from 211 FIA plots (P3 down woody materials) from North Carolina, Virginia, and West Virginia, measured in 2003 to 2005 (FIA 2007b). Precise comparison is difficult because Woodall and Williams' density values are given by species and our values are summarized into groups of predominant species. Although we averaged Woodall and Williams' values according to our species groups, this does not necessarily mean that species mixtures were consistent between data sources for the comparison.

For duff, we found that using Woodall and Williams' data estimated more mass than when either our bulk density calculations or our model was used (except for the oak group), and estimates of litter mass using their data were lower than our estimates (except for the hardwood group) (Figure 4). For both duff and litter, our regression model (including bias correction) always estimated less mass than when our calculated density values were used. A plausible explanation for this is that the mean density calculations overestimate because of the inverse J-shaped relationship that we observed in calculated density versus depth (Figure 3); that is, density varied with thickness of the duff and litter layers. Mean density (and thus mass) may be overly influenced by the samples from smaller depths (which have larger density values, whether real or from error propagation). On the other hand, predictions from our regression when converted to density ($D = M/V$) do a reasonable job of modeling the depth trend found in the data (Figure 3). Because estimates using the mean calculated bulk density ignore this trend, it seems more reasonable to use the simpler regression. Speculation as to why estimates using Woodall and Williams' data were generally different from ours is not meaningful because there are too many unknown factors between studies, such as the scope of data collection and possible mismatches in species groups.

Although our data sample was small, our results do illustrate that the regression model offers much promise for summarizing FIA P3 soils if FIA were to start separating duff from litter in the field for laboratory processing of the respective material layers. From these separated measurements, data regression models could be developed for all FIA forest types.

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