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Evaluation of Techniques for Determining the Density of Fine Woody Debris

Becky Fasth
Mark E. Harmon
Christopher W. Woodall
Jay Sexton

Abstract

Evaluated various techniques for determining the density (i.e., bulk density) of fine woody debris during forest inventory activities. It was found that only experts in dead wood inventory may be able to identify fine woody debris stages of decay. Suggests various future research directions such as development of a 2-class fine woody debris decay class system.

Cover Description

Pine (*Pinus* spp.) fine woody debris along California coast. Photograph by Chris Woodall, U.S. Forest Service.

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INTRODUCTION

For this study, fine woody debris (FWD) was defined as downed and dead woody debris less than 7.62 cm in diameter (Woodall and Monleon 2008). FWD is one component of forest detritus that is critical to numerous scientific/ecological fields such as carbon accounting (Woodall et al. 2008), wildlife habitat assessment (for examples, see Maser et al. 1979, Harmon et al. 1986, Bull et al. 1997), and fuel loading estimation (Lutes et al. 2006, Rollins et al. 2004, Van Wagner 1968, Woodall and Monleon 2008). Detritus provides a diversity (stages of decay, size classes, and species) of habitat for fauna ranging from large mammals to invertebrates (Bull et al. 1997, Harmon et al. 1986, Maser et al. 1979). Plants use the microclimate of moisture, shade, and nutrients provided by deadwood to establish and regenerate (Harmon et al. 1986). Due to the possibility of dwindling deadwood habitat for native species and increasing fuel loadings across the United States, comprehensive large-scale inventories of downed deadwood including FWD have been established for habitat assessments/wildlife conservation efforts and fire hazard mitigation efforts (for examples, see Marshall et al. 2000, Ohmann and Waddell 2002, Rollins et al. 2004, Tietje et al. 2002, Woodall and Monleon 2008). Worldwide, there has been increased effort during past years to inventory deadwood resources to address greenhouse gas offset accounting and biodiversity concerns (Kukeuv et al. 1997, Woldendorp et al. 2004, Woodall et al. 2009). Therefore, refining estimates of FWD population attributes (e.g., biomass) is a critical component of nationwide efforts to quantify carbon stocks and wildfire hazards.

FWD is a forest ecosystem attribute that can be rather difficult to assess due to its relatively small size, ephemeral nature, states of decomposition/fracture, and heterogeneous spatial orientation within forest sites. FWD may be inventoried by areal sample plots where all FWD is collected and weighed to determine a fairly accurate population estimate. Such sample methods are very time-consuming given the sample collection and lab-processing methods. Additionally, such collection methods disturb permanent sample plots confounding future remeasurement activities. An alternative to the aerial sampling of FWD is the use of line-intersect sampling (LIS) methods where FWD population attributes are estimated based on the probability of FWD pieces intersecting sampling transects. FWD volume may be estimated using LIS estimators; however, coefficients representing the bulk density and carbon content for FWD must be incorporated into FWD LIS estimators to estimate such attributes. Downed dead wood pieces in advanced stages of decay may have lost most of their original density (Harmon et al. 2008). Given that most national downed dead wood inventory programs lack sample methods for determining FWD decay status (Woodall et al. 2009), development of rapid field techniques for determining such attributes could refine FWD biomass estimation procedures.

The Authors

BECKY FASTH is a senior faculty research assistant with the College of Forestry, Oregon State University, Corvallis, OR 97331.

MARK E. HARMON is a professor and Richardson Chair with the College of Forestry, Oregon State University, Corvallis, OR 97331.

CHRISTOPHER W. WOODALL is a research forester with the Northern Research Station, U.S. Forest Service, St, Paul MN 55108.

JAY SEXTON is a senior faculty research assistant with the College of Forestry Science, Oregon State University, Corvallis, OR 97331.

Fine woody debris is inventoried nationwide by the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service in order to determine FWD biomass within particular forest conditions or domains (e.g., an entire state or forest type) (Woodall and Monleon 2008). Current field data procedures consist of tallying FWD by size class along line-intersect sampling transects within FIA plots (for details, refer to Woodall and Monleon 2008). These counts of individual FWD pieces are then summed and an estimate of volume is determined using quadratic mean diameters. Biomass conversion constants published in the literature are currently used to convert volume to biomass (see Harmon et al. 2008). For downed dead wood with a transect diameter over 7.62 cm (coarse woody debris, CWD), a decay class is qualitatively determined for every piece. Two constants are used during CWD biomass estimation: (1) the species-specific initial density (i.e., specific gravity in g/cm^3) and (2) a decay reduction factor for each decay class that accounts for the decline in density as this form of detritus decomposes (Harmon et al. 2008). Because FIA does not determine the decay class or the species of each FWD piece, the initial FWD bulk density is based on a mean of bulk densities for the constituent tree species in the plot's forest type (see Appendix 7.4 in Woodall and Monleon 2008). Additionally, only one decay reduction factor is used for all FIA plots across the U.S. Previous analyses have indicated that when the FWD decay reduction factor is actually measured for a species the uncertainty of biomass is 1 to 3 percent (Harmon et al. 2008). In contrast, when the decay reduction factor has to be estimated, the uncertainty of FWD biomass estimation may range from 12 to 19 percent (Harmon et al. 2008). A more systematic sampling of FWD density (i.e., decay status) would be optimal to refine FWD biomass estimation and subsequent carbon stocks nationwide, especially to increase the power of detecting FWD biomass loss and subsequent carbon flux.

When decay stage-specific density is coupled with the volume estimates in each decay class, one can potentially estimate the biomass of woody debris with more certainty. The work that has been done with CWD has shown that species have different patterns of density decline associated with decay classes (Yatskov et al. 1992). The change in density of FWD over time due to decomposition might be accounted for by establishing various decay classes of FWD and determining the density of each decay class. Classes can be defined by the presence of criteria that tend to be associated with certain decay stages. An important caveat is that there can be a great deal of variation within and between pieces of decomposing wood that may cause misclassification by some individuals and introduce additional uncertainty. There is also the question of whether FWD can be inventoried on permanent sample plots in a way that will allow the use of decay class specific densities without excessively increasing field crew effort. If using empirically derived FWD decay classes can reduce the uncertainty of FWD population estimates (e.g., biomass), the evaluation of FWD decay measurement techniques is warranted.

OBJECTIVES

The goal of this study was to evaluate sample techniques for determining the density of FWD within the context of FIA's national inventory of downed woody materials. Specific objectives were to (1) determine whether qualitative differences in FWD states of decay have resulting significant differences in wood density, (2) identify characteristics of FWD that could enable a FWD decay class system, and (3) determine to what extent field crews are able to consistently identify decay classes of FWD and the effects of decay class measurement repeatability on subsequent FWD population estimates.

Courtesy of Becky Fasth, Oregon State University

Figure 1.—First sample site (approximately 40 years old) harvested in 2007, Oregon State University's McDonald-Dunn Research Forest, Willamette Valley, Oregon.

Courtesy of Becky Fasth, Oregon State University

Figure 2.—Second sample site, a second-growth mixed conifer stand (approximately 40 years old), Oregon State University's McDonald-Dunn Research Forest, Willamette Valley, Oregon.

METHODS

Study Sites

Two stands were chosen at Oregon State University's McDonald-Dunn Research Forest. The first was harvested in 2007 (Fig. 1), and the second was a second-growth mixed conifer stand, roughly 40 years old (Fig. 2). The McDonald-Dunn Research Forest consists of about 11,250 acres of predominantly forested land on the western edge of the Willamette Valley in Oregon and on the eastern foothills of the Coast Range. The forest is somewhat isolated topographically from the rest of the Oregon Coast Range, residing in the rain shadow created by it. The forest is dominated by Douglas-fir, western hemlock, and western redcedar.

Initial FWD Decay Class System

A system currently exists for determining decay classes of CWD (Harmon et al. 1986, Maser et al. 1979), but none yet exists for decay classes of FWD other than green versus decayed. Based on characteristics typically used to ascertain classes of CWD decay, an extensive list of FWD characteristics (e.g., presence/absence and visual characteristics of the leaves, bark, and wood) was used to develop an initial FWD decay class system:

> Decay Class 1 (DC1): Fresh FWD with leaves or twigs present; appearance of recent fall, complete bark cover that is usually shiny in appearance
>
> Decay Class 2 (DC2): Not quite fresh FWD with no leaves but sometimes twigs present, complete bark cover that is usually dull in appearance
>
> Decay Class 3 (DC3): FWD that seems to have been on forest floor for some time, may be incorporated into the forest floor and moss layer, with significant bark loss and possibly wood loss (starting to decompose)
>
> Decay Class 4 (DC4): Sample very decomposed and incorporated into the forest floor with no bark and surface wood eroded from decomposition

Table 1.—Number of samples collected and classified by three experts on each sample site

Decay class	Harvested	Mixed conifer
1	22	6
2	16	10
3	20	25
4	4	5
Total	62	46

Table 2.—Characteristics used to classify the decay for each fine woody debris sample

Characteristics	
Green needles present	Brown rot present
Moss and Lichen present	White rot present
Fungi present	Bright wood
Shiny bark	Dull wood
Dull bark	Sapwood fragmenting
Bark loss	Solid core remains
Chipping bark	Sample dark and rotten
No bark	

Collection of FWD Samples

The two separate study sites allowed limited evaluation of FWD decay class efficacy between and within stands. Three experts in identifying CWD decay classes entered each study site and collected samples of FWD according to the study's FWD decay class system. Samples of FWD were randomly collected throughout each study site and placed by decay class into individual 5-gallon buckets for transport back to the laboratory. We tried to collect at least 20 samples of each decay class from each forest stand, but this was not always possible. For example, we were unable to find enough of decay class 4 in either stand, and decay classes one and two were difficult to locate in the mixed conifer stand. A total of 62 samples were collected from the clearcut harvested stand and 46 samples were collected from the mixed conifer stand (Table 1). The FWD samples were cut to a length of 35 cm or less so that they would fit lengthwise into the sample bucket. The physical characteristics of each sample were recorded (Table 2). Random pieces of each decay class of FWD were also broken by hand to determine if the decay classes broke in a characteristic way and how the wood appeared once broken (e.g., splintered break, clean break, bending break, dark or light wood, rotten core).

Determination of Individual FWD Piece Densities

The species (Table 3), mean diameter, and total length were recorded for each sample upon return to the laboratory. The green volume for each FWD piece was determined, assuming the piece was a cylinder, given the total lack of FWD volume equations in the literature. We acknowledge the FWD volume equation knowledge gap and suggest it be studied further. Following "green" measurements, the FWD pieces were individually weighed, put into paper bags, and oven-dried at 55 ^{o}C. When the weight of the samples had stabilized (i.e., the

Table 3.—Number of fine woody debris samples by species and study site

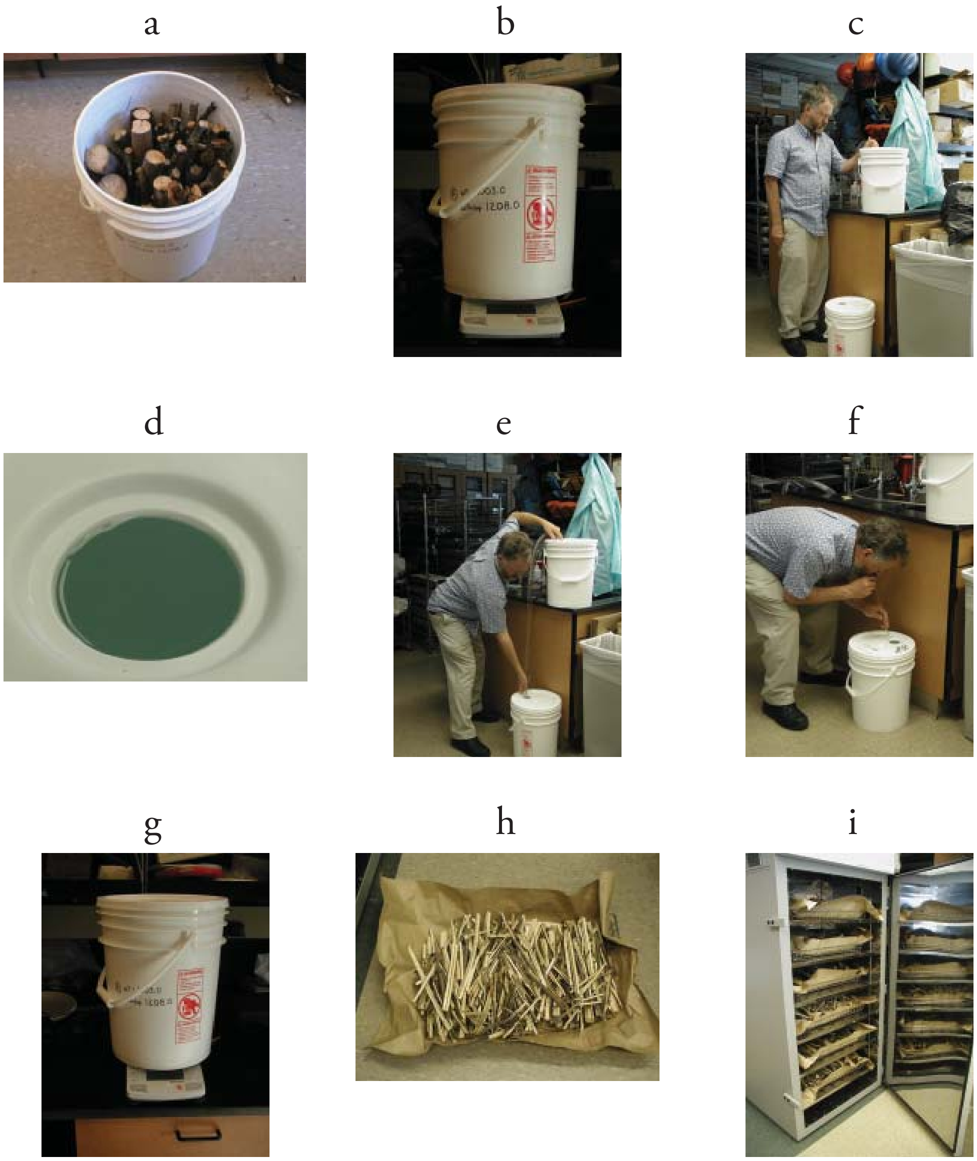
Species	Harvested	Mixed conifer
Acer circinatum	1	
Acer macrophyllum	8	19
Prunus emarginata	1	
Pseudotsuga menziesii	28	21
Quercus garryana	6	
Unknown hardwood	4	
Unknown	14	6

samples were no longer losing moisture), they were weighed again to obtain the dry weight. Density was calculated as dry mass divided by green volume for each individual FWD sample for a total of 108 density measurements. Sample collection and processing time (drying time excluded) was cumulatively ≈ 3 days.

Determination of FWD Density by Decay Class Using Water Displacement

Using the FWD samples from the FWD piece density analysis, the next step in the lab was to lightly clean the FWD pieces of lichen and moss (Fig. 3). The FWD pieces were then placed in a sample bucket whose weight had already been tared on a scale. The bucket and branches were weighed together to determine the total field wet weight of all of the samples within the bucket. A hardware cloth circle of known weight was placed across the top of the branches (to avoid loss of FWD materials during water displacement procedures) and the top of the bucket was sealed down. The bucket was then filled with water and the branches were soaked for 15 minutes to decrease the error in volume created when the samples absorb instead of displace the water. The water was then poured off; the bucket was opened; and with the mesh circle held in place, the bucket was tipped to pour off any remaining water. The bucket, top, mesh, and samples were re-weighed after soaking and the weight was recorded. A second identical sealed bucket was filled with water until the water level produced a meniscus at the middle of the open pour hole located on the bucket lid. A length of tubing was used to siphon the water from this water supply bucket into the sealed sample bucket. When the water level was near the top in the sample bucket, smaller diameter tubing was used to siphon the last water needed to fill the sample bucket to the same level to which the water supply bucket had been filled. A pipette was used to fine-tune the water level so that the meniscus fell precisely at the middle of the open pour hole. The water supply bucket was then weighed to determine how much water remained, which was equal to the volume displaced by the FWD in the sample bucket. The weight of the bucket and top was subtracted from the weight of the entire water-filled bucket to determine the weight of the water displaced by FWD. To reduce the error due to water absorption into the branches during the volume determination, this amount was measured by emptying the sample bucket in the same way as was done after the pre-soaking. The bucket, top, mesh, and branches were then remeasured, and the difference between this new weight and the weight recorded before the volume determination was added to the weight of the displaced water to correct for absorption. The volume measurement was done three times in succession, and the average of the three determinations was recorded as the volume of the FWD samples. The process was repeated for each decay class.

The water displacement process was also performed with 250-ml square Nalgene plastic bottles of known volume to ascertain the precision and repeatability of the volume determinations. Three volume determinations were done with 10 bottles, 3 with 15 bottles, 11 with 20 bottles, and 1 with zero bottles. To test the precision and repeatability of the whole procedure including the volume of water absorbed by wood, 35 wood blocks of known volume were put through the same process as the FWD. Volume determination with the wood blocks was repeated 10 times in the same buckets used for FWD analysis. Precision of the volume determination ranged from 96 to 99 percent of the true volume.



All photos courtesy of Becky Fasth, Oregon State University

Figure 3.—Steps in measuring fine woody debris water displacement: (a) Field collection of a single decay class in a sample bucket, (b) field wet weight recorded, (c) fine woody debris wetted for 15 minutes then sample bucket completely emptied and re-weighed, (d) 20L water supply bucket filled until meniscus at mid-point of pour hole, (e) water siphoned from water supply bucket to lower sample bucket, (f) volume adjusted by pipette to proper meniscus location, (g) water supply bucket containing water displaced by branch volume re-weighed, (h) branches split to facilitate drying, and (i) branches dried to stable weight.

After volume determination, the branch samples were removed from the bucket and split with chisels, clippers, or an axe to facilitate drying in an oven. Care was taken to avoid loss of biomass due to violent fracturing and the scattering of wood dust. The samples were dried in the oven at 55 ^{o}C for a week, until their weight stabilized. At this point the oven-dry weight of the entire bulk sample was recorded for one FWD decay class. Total dry weight divided by total volume was used to calculate an average density of all the pieces in the bucket. Additional samples from each decay class present in the stand were processed in the same manner. Sample collection and processing time (drying time not included) per stand was cumulatively ≈ 2 days.

Field Crew Identification of FWD Decay Classes

The final study objective was to determine if people could consistently identify pieces of FWD by decay class in the field. This objective was accomplished in three parts starting with the potentially most precise and time consuming and finishing with the potentially least precise and least time consuming:

1) Assessment of decay class of individual pieces along a transect
2) Assessment of percentage of pieces in each decay class on a 2 by 2 m quadrat
3) Assessment of the percentage of pieces in each decay class in a visual circle around the field crew

Courtesy of Becky Fasth, Oregon State University

Figure 4.—Individual tagged pieces of fine woody debris.

In part one, CWD decay class experts located 80 pieces (samples) of FWD in varying stages of decomposition in the mixed conifer stand and placed them along a transect (200 m). All of the samples were flagged with ribbon and labeled with a pin flag numbered 1 through 80 (Fig. 4). Twenty participants were recruited to traverse the transect and record a decay class for each sample. Each participant repeated the entire transect after performing parts two and three of this investigation. We hoped that by not repeating the transect immediately a participant would have fewer chances to remember the decay class recorded on the first walkthrough. The repetition was done to determine repeatability and variation within a single observer. Of the 20 participants, 3 were experts at CWD decay class identification, 2 had previous experience in CWD decay class identification, 10 had previously worked in forests, and 5 were random high school students. The approximate time spent by a participant in assessing and recording a decay class was from 2 to 5 seconds per sample. The following information was given to test participants about decay class differentiation:

DC1: Fresh, fine twigs, possibly with needles or leaves; bark intact, no sign of rot

DC2: Not fresh, some loss of twigs or bark, no loss from rot, some changes due to age

DC3: Most fine twigs gone, significant bark loss, some outer surface erosion, still strong, may be incorporated in the forest floor

DC4: Little bark, fully colonized by rot, loss of strength, incorporated in the forest floor

After all participants had completed the transect, the samples were collected and returned to the lab where mean diameter, length, and oven-dry weight were recorded and used to determine the true density of each sample. The "true" decay class for each sample was determined to be the consensus decay class of the expert determinations, when two or three of the three experts recorded the same decay class for a piece. A mean wood density by expert consensus decay class was then calculated and termed the mean consensus wood density for that decay class. The overall mean stand wood density was calculated by determining the mean wood density of all 80 samples. We should note that the FWD pieces collected for this study objective were separate from FWD pieces collected for study objectives one and two.

For the second part of the study, we were interested in determining whether our 20 participants could consistently record decay class abundance (percent of each decay class) within a fixed-area plot. Eight 2 by 2 m plots were established in the mixed conifer stand and the corners were marked with pin flags. Participants were asked to record the percentage of each of four decay classes that they believed were present within each of the eight plots. The time spent by each participant at each plot was about 1 minute. Samples were collected from this location and treated as in the previous section on determination of individual FWD piece densities to determine the actual density for these plots.

In the third part of the study, participants were asked to stand in three different spots in the mixed conifer stand and record percentages of decay classes of FWD they believed were present for everything visible (visual circle) within the forest stand. As with the fixed-area plots, the time spent by each participant at each circle was about 1 minute. Samples were collected from this general location and treated as in the previous section on determination of individual FWD piece densities to determine the actual density for this stand.

To estimate a weighted average wood density of each observer for the transect, small plots, or stand, the percentage of pieces in each decay class was multiplied by the average wood density for that decay class. These products were then summed for all decay classes and divided by 100 to calculate the average wood density for each observer. The density of the decay classes was an average from two sources: the individual pieces collected and bulk density as determined by water displacement.

Mean stand wood density generated from each of the methods in this study was compared to the mean stand wood density generated using the methods sometimes employed by the U.S. Forest Service where two values for density ("fresh" and "decayed") are currently used to calculate mass of FWD from the volume data collected on the plots. For this comparison, the "fresh" materials were those assigned to decay class one and the "decayed" pieces were those assigned to decay classes two, three, and four. The fresh and decayed values for *Pseudotsuga menziesii* (0.57 and 0.43 g/cm^3, respectively) from Harmon et al. (2008) were used because it is the dominant species in the mixed conifer stand examined. The expert consensus decay classes were used to generate a mean stand wood density, and the non-expert decay class determinations were used to calculate the range of potential values.

Where appropriate, ANOVA (GLM procedure in SAS) was used to test significant differences between the density of FWD decay classes.

Table 4.—Number of samples in harvested study site listed by the physical characteristics used to classify decay

	Decay class			
Characteristic	1	2	3	4
Shiny bark	22	4		
Bright wood	22	11		
No bark		1	3	4
Bark chipping		1		
Moss and lichen		9	10	
Brown rot			1	4
Bark loss			17	
Sapwood fragmenting			20	
Solid core remains				4

Table 5.—Number of samples in mixed conifer study site listed by the physical characteristics used to classify decay

	Decay class			
Characteristic	1	2	3	4
Green needles	1			
Moss and lichen	4		20	1
Shiny bark	5			
Bark loss		1	16	
No bark		1		5
Dull bark		3	23	
Bark chipping		7		
Solid core remains			1	3
Brown rot			1	
White rot			1	
Fungi			2	1
Dark/rotten			2	5
Bright wood			2	
Sapwood fragmenting			5	5
Dull wood			15	

RESULTS

Physically Identifiable Characteristics of Decay Classes

The presence of needles/leaves and shiny bark were fairly consistent indicators of decay class one in FWD in both the harvested and mixed conifer stands (Tables 4 and 5). Bright wood at breaks was also a strong indicator of decay class one in the harvested stand, but not in the mixed conifer stand. Decay class two showed no clear and decisive physical characteristics except that the bark was falling off; instead, it shared many of the same characteristics of both decay class one and decay class three. In the mixed conifer stand, the presence of moss/lichen, bark loss, dull bark, and dull wood was consistent throughout most samples for decay class three. In the harvested stand, however, bark loss and sapwood fragmentation were the main characteristics for decay class three. In both forest stands, decay class four shared many characteristics with decay class three, yet could be distinguished by having dark rotten wood, a solid core, and no bark.

Wood Density—Decay Class Relationships

Densities by decay class of multiple individual samples of FWD collected by experts

Wood density values decreased significantly (p-value 0.0130) as decay class increased based on the mean of samples from the mixed conifer stand (Fig. 5). This was not the case in the harvested stand where wood density values stayed level and even increased as decay class increased. The p-value 0.0613 is suggestive of a difference, but not as significant as in the mixed conifer stand. There was weak statistical difference (p-value = 0.0993) between the mean wood density by decay class of the harvested and the mixed conifer stands. All wood density values, particularly decay class three, demonstrated overlap with adjacent decay classes in both the harvested and mixed conifer stands. When all samples from both stands (mixed conifer and harvested sites) were combined to create an overall mean wood density by decay class, there was a significant difference (p-value = 0.0008) between FWD decay classes with decreasing wood density with increasing decay class until class four, in which the wood density increased slightly. The mean overall wood density combining stands and decay classes was calculated to be 0.457 g/cm^3 (n=108). The unbalanced distribution of FWD decay class samples suggests that this overall mean could be slightly biased toward fresher decay classes; however, given the lack of highly decayed FWD pieces in forest ecosystems, this may represent reality.

Densities of bulk samples of FWD using water displacement

When water displacement was used to determine a mean bulk density for each decay class, there was a clear trend of decreasing density with increasing decay class (Fig. 6) (p-value 0.0447 moderately suggestive that the means are different). The mean overall stand density for this method of density determination was calculated to be 0.468 g/cm^3.

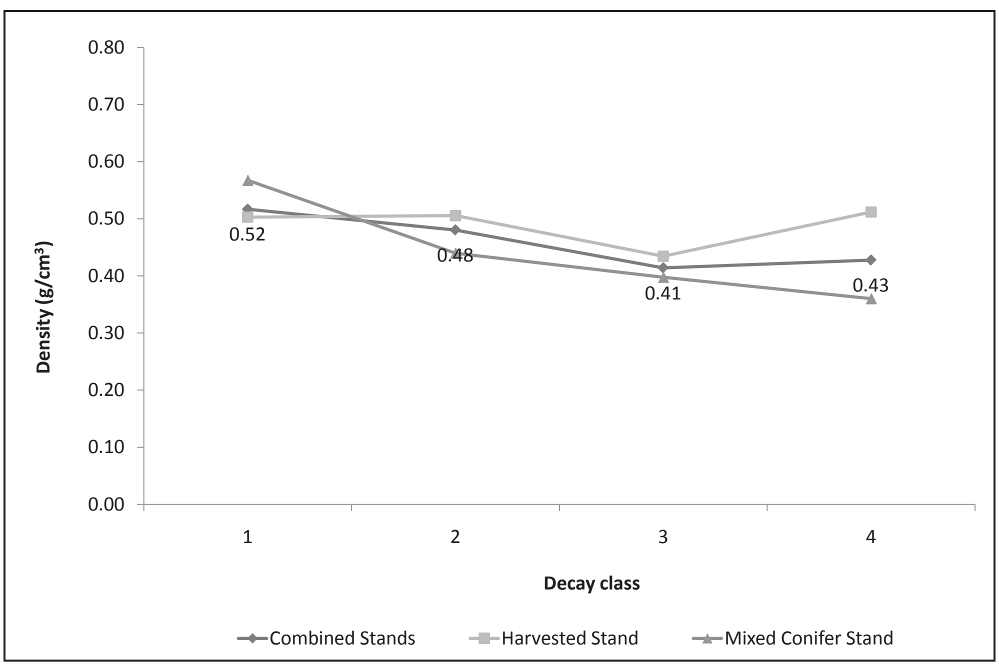


Figure 5.—Mean density of fine woody debris by decay class in separate stands and combined.

Field Crew Identification of Decay Classes

Decay class identification and density along a transect

There was a noticeable difference between an expert's consistency in identifying decay classes of FWD and that of the non-experts. Although the three experts did not agree on every sample of FWD along the transect, they did not vary by more than one decay class from the mean (Fig. 7). The non-expert observers, however, ranged one to two decay classes different

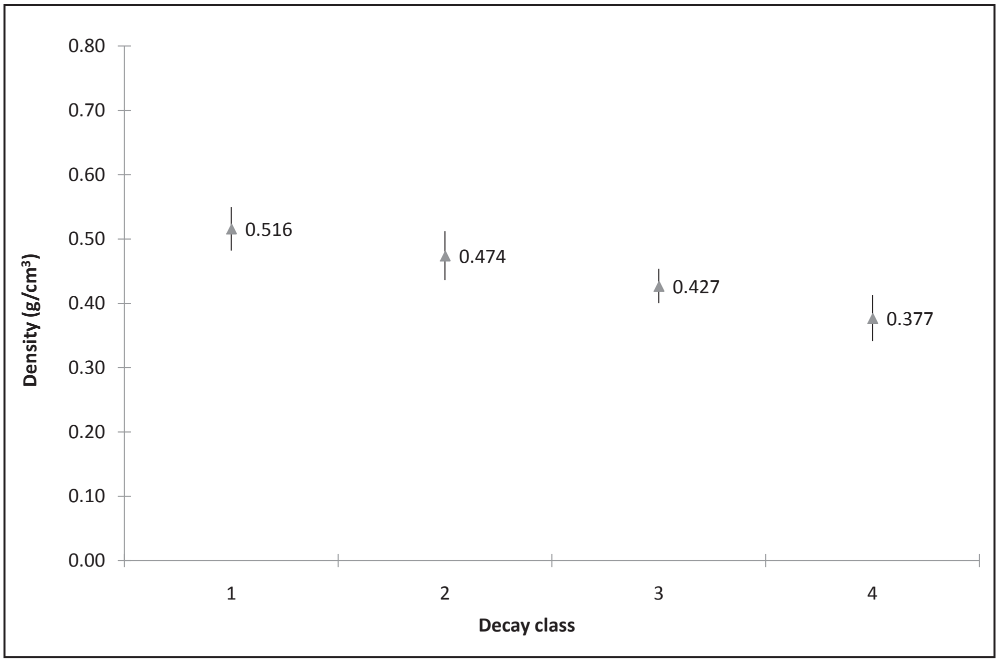


Figure 6.—Mean density and associated standard errors of fine woody debris by decay class for water displacement method.

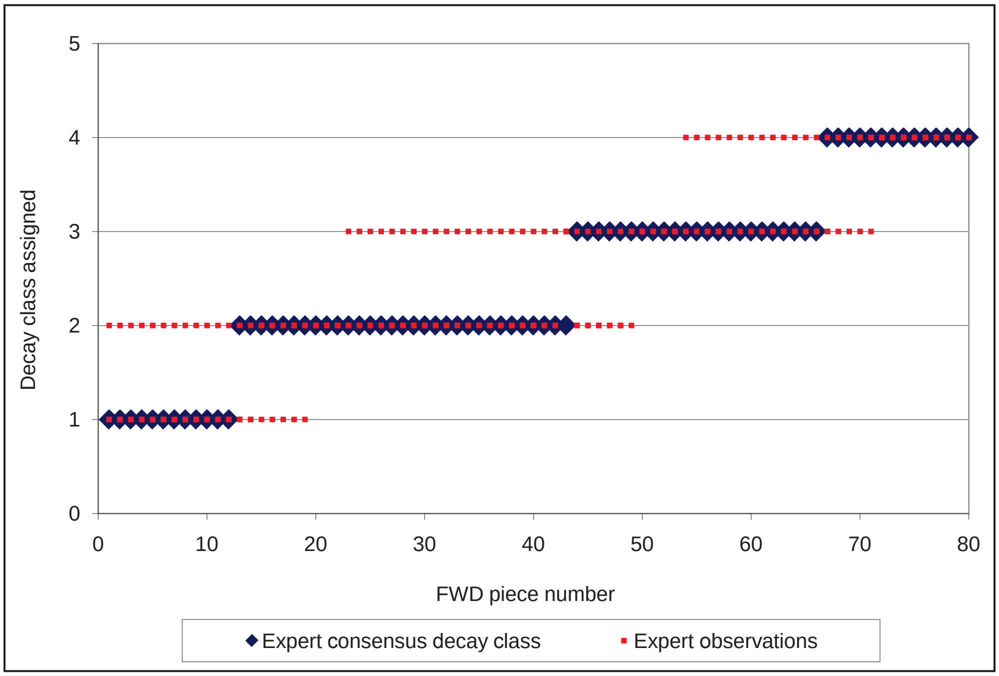


Figure 7.—Expert consensus fine woody debris decay class and recorded decay class for 80 pieces along transect.

from the expert consensus decay class (Fig. 8). For decay class two and three, non-expert observers recorded any one of the four decay classes. The mean wood density by expert consensus decay class had a trend of decreasing density with increasing decay class (Fig. 9). The mean overall stand wood density for all of the samples on the transect was 0.433 g/cm^3.

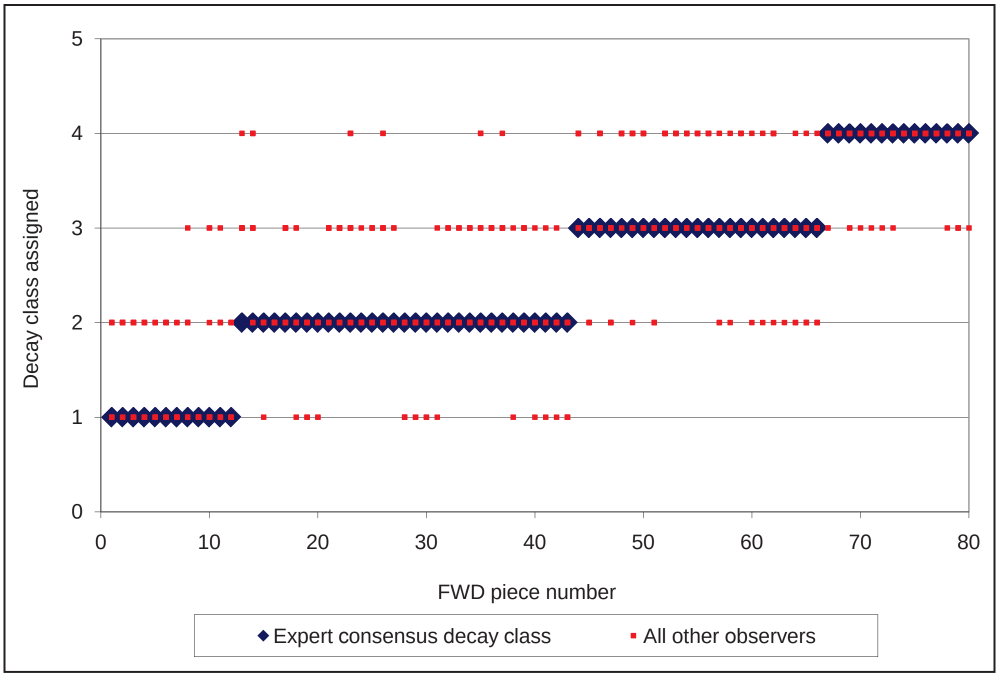


Figure 8.—Expert consensus decay class and all other observer recorded decay class for 80 pieces along transect.

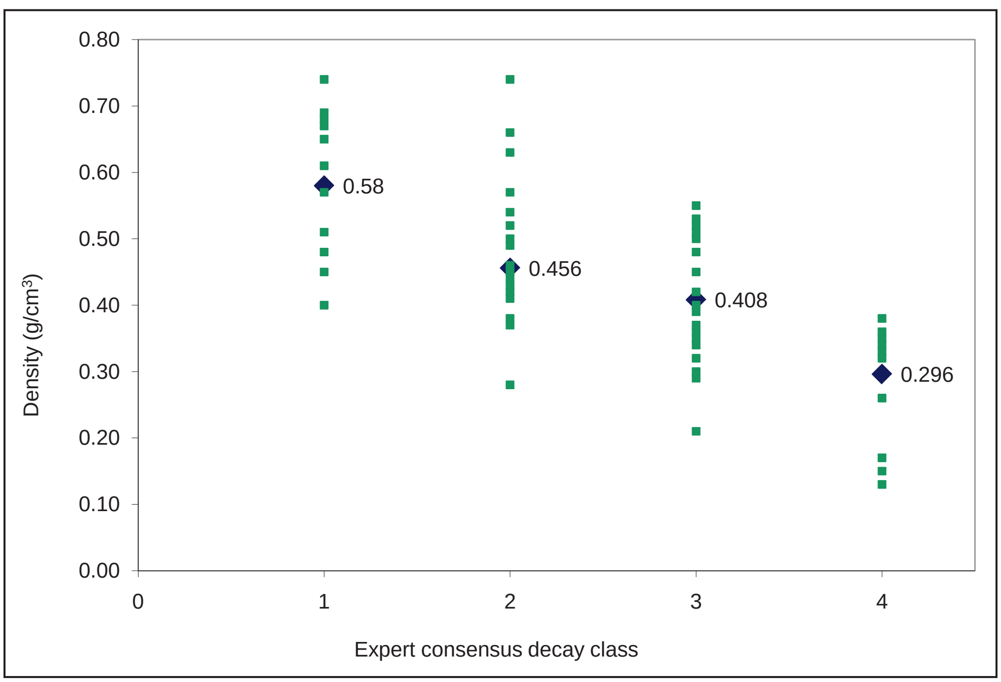


Figure 9.—Density and mean of transect samples by expert consensus decay class.

Decay class abundance identification and wood density within fixed-area plots and visual circles

There was no consistent pattern or agreement between the 27 observations made within the fixed-area plots and visual circles to determine decay class abundance. Multiple observers were unable to look at an area and determine percentages of each decay class with any sort of agreement (Figs. 10 and 11). Although there was no agreement among the observers, some minor patterns emerged within the stand overall. There was a tendency to record a higher

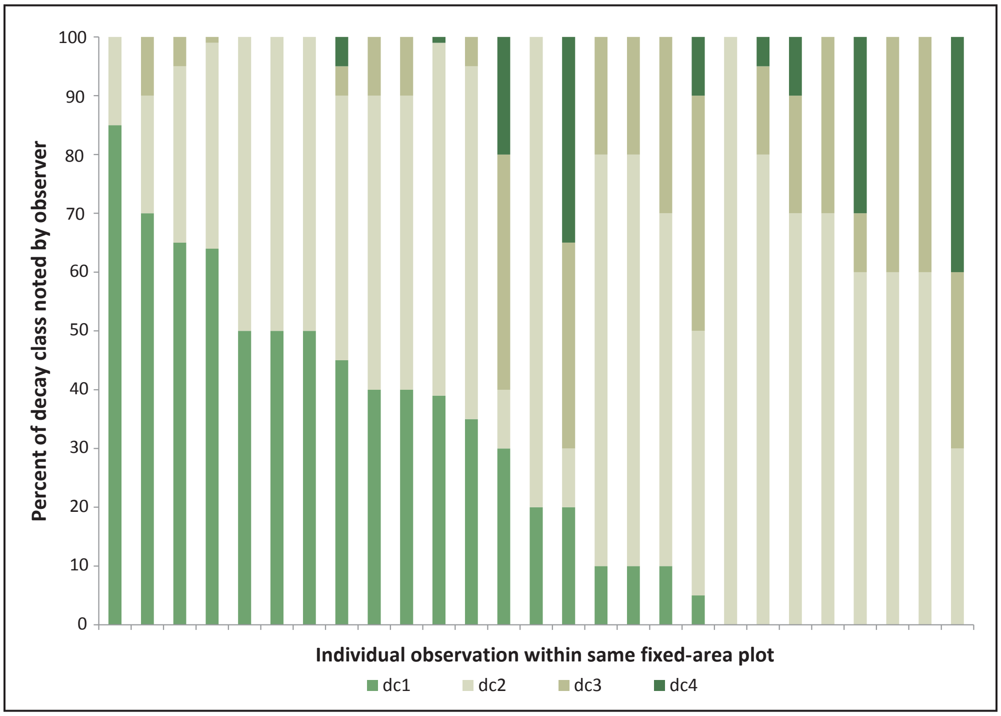


Figure 10.—Percent of decay class noted for all observers in fixed-area plot 1.

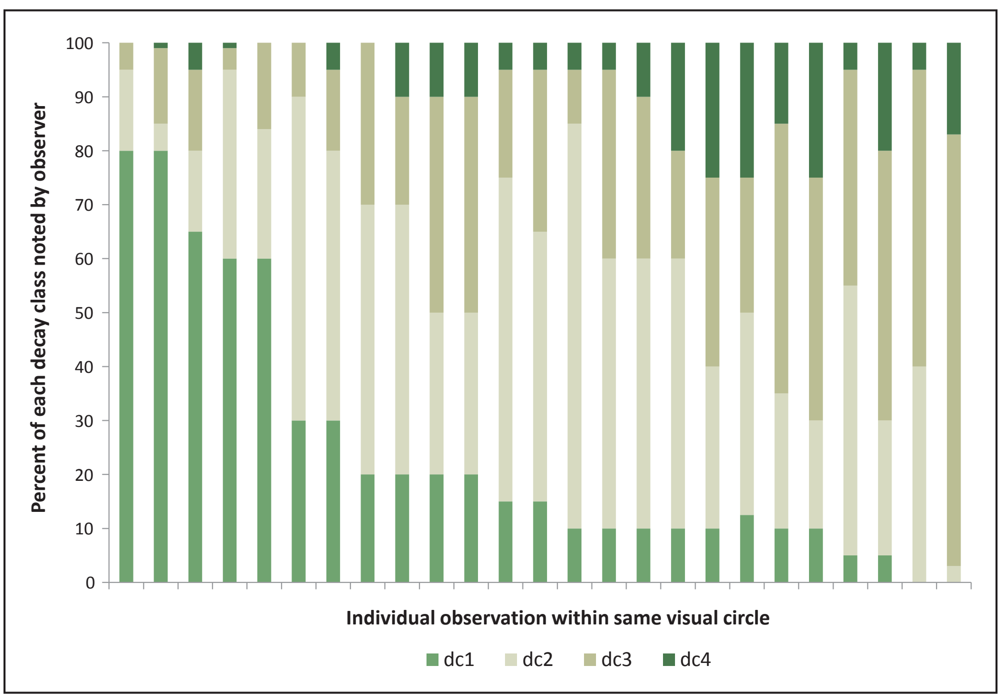


Figure 11.—Percent of decay class noted for all observers in visual circle 1.

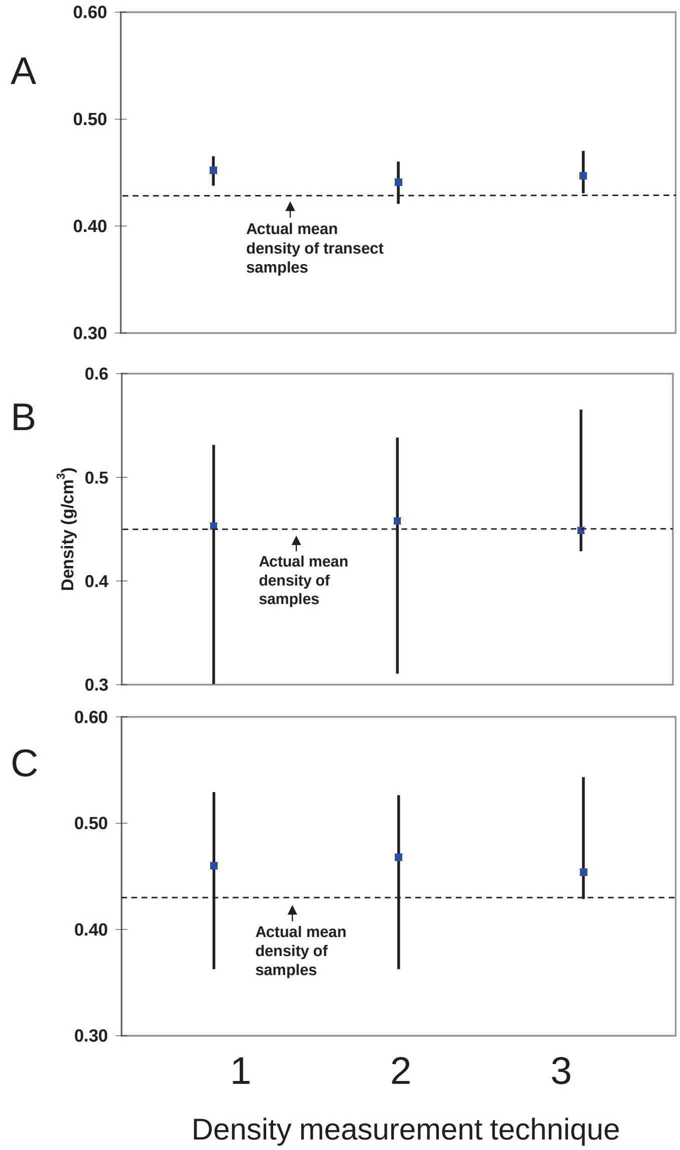


Figure 12.—Density by decay class from (1) individual samples, (2) water displacement, and (3) Harmon et al. (2008) applied to decay class abundance recorded on (A) the transect, (B) fixed-area plots, and (C) visual circles. Solid black line shows range of results, blue box is mean of all observations, and dashed line is measured stand mean for that area.

percentage for decay class two than other decay classes and a much lower percentage for decay class four in both the fixed-area plot and visual area circle. It is doubtful that this pattern would be detectable with fewer than 10 observations using either method.

When the wood densities by decay class from individually collected samples, water displacement samples, and currently accepted method (Harmon et al. 2008) were used to determine a total stand mean FWD density for all observers along the transect sample, the mean stand density ranged from 0.42 to 0.47 g/cm^3. The actual measured wood density of all samples on the transects was 0.43 g/cm^3 (Fig. 12). When the same densities were applied to the percentage of decay class abundance for each of the fixed area plots, there was a wider spread of possible densities ranging from 0.30 to 0.54 g/cm^3 depending upon which fixed area plot and which observer are being considered (Fig. 12). The actual mean measured density of samples from the fixed area plots was 0.453 g/ cm^3. Again, when the same densities were applied to the percentages of decay classes in visual area circles, the densities ranged from 0.36 to 0.53 g/cm^3 (Fig. 12). The actual mean measured density of samples from the visual area circles was 0.43 g/cm^3.

DISCUSSION

The implications of this study's results are restricted due to the limited spatial scope of this study (Pacific Northwest of the United States) and lack of replication among the two disparate study sites (harvested versus mature mixed conifer). The numerous inconclusive results of this study suggest that a large number of replicated study sites across the diverse forest ecosystems of the U.S. are necessary to reach a level of certainty for affecting the national FWD sampling scheme used by FIA. This important caveat aside, the results of this study can be used as an indicator regarding future study designs and the possible benefits of refined FWD sampling procedures.

Can a FWD decay system, besides undecayed versus decayed, be developed? The results from this study suggest that a comprehensive list of numerous decay attributes can be developed and readily trained/employed in the field. There is abundant literature on CWD decay attributes of classification schemes. Is the FWD decay classification scheme repeatable with distinct differences between stages of decay? This study indicates that the FWD decay classification scheme is probably only repeatable among highly trained forest detritus experts. The amount of uncertainty of the mean stand density estimate based on the decay class determination of a non-experienced crew member was greater than the measurement repeatability tolerance (± one decay class) of the national CWD inventory conducted by FIA (Westfall and Woodall 2007). Unless substantial training is undertaken, the reliability of the decay class determination would be highly questionable. There is so much overlap in FWD decay characteristics among the classification scheme that novices or even typical forest inventory field crews would not be able to repeat FWD decay class assessments. There was a tendency for FWD decay classes one and two to differ in attributes compared to FWD in decay classes three and four. There is a slim possibility that forest inventory field crews could be trained to identify proportions in undecayed (decay classes one and two) and decayed (decay classes three and four) FWD.

If FWD could be accurately assigned to decay classes, what difference would it make in eventual population estimates? The answer to this question hinges on the premise that the expert CWD scientists in this study accurately assigned FWD into correct classes of decay. This is the ultimate confounding factor when developing any FWD decay class study. With this caveat aside, expert opinion was used in this study because if an expert couldn't separate FWD pieces into decay classes with significant differences in density then there is little chance that field crews could. There was significant difference in FWD density, with density decreasing as stage of decay increased. Does this significant difference affect population estimates? Consider this example: if the volume of FWD on a particular FIA plot is 5 m^3/ha, then the resulting biomass estimate using the most precise overall stand density (individually measured FWD) would be 22.8 Kg/ha. If we used the same scenario and the density values from water displacement, the calculated stand FWD biomass would be 23.4 Kg/ha. When FWD density is based on currently used techniques (FWD forest type table, Harmon et al. 2008, Woodall and Monleon 2008), the calculated stand biomass is 22.5 Kg/ha. Given the additional measurement errors incurred by having field crews assess FWD states of decay and lab analysis of FWD density, it would be difficult to suggest that a FWD decay class system would substantially refine eventual FWD population estimates.

Given the limited possibility of improving the precision of FWD biomass estimates using a FWD decay class system, did this study's techniques require a lot of time? The range of density was much narrower when the decay class of each piece of FWD was estimated, but this took up to 15 seconds per FWD piece. It took 15 to 20 minutes to complete a piece by piece classification along a transect with 80 FWD pieces. Results were not significantly different between a fixed-area plot and a total visual area circle when percentages of FWD decay class abundance were recorded. Each fixed-area plot or visual circle took roughly 1 minute to complete. The main difference was a higher percentage of decomposed FWD recorded in the fixed-area plots as compared to the visual circles. Although not a time-consuming endeavor for visual circles, this study's objectives and scope would have to be substantially expanded to confirm increases in the precision of FWD biomass estimates before even a few minutes per plot would be added to FIA field crew time. The collection of spurious FWD decay class information, despite just a few minutes per plot, might impart unjustified additional certainty to FWD estimates.

Finally, is there a superior lab method for determining FWD density? Two lab methods were explored in this study: individual piece measurement and water displacement. Neither method had results that indicated supremacy. Both methods required the diligent collection of FWD pieces, enough to fill relatively large buckets. The water displacement methodology required less individual handling of FWD pieces, so it might be optimal in that particular context. However, the water displacement of highly decayed FWD pieces introduces the possible measurement error of siphoning off of FWD decayed wood dust and chunks. The effort required to estimate FWD density using lab methods on an individual inventory plot is beyond the time limitations of most field crews.

CONCLUSIONS

What can be suggested for the future? First, there appears to be no FWD sample protocols readily available that would refine the FWD biomass estimation procedures currently used by FIA. The results of this study indicated through time-consuming work that there are significant differences in density across stages of FWD decay. Only an expert can identify these differences that don't result in a substantial difference in estimates of FWD biomass. Second, expanded research in the area of developing a decayed versus undecayed FWD classification scheme is suggested, especially if non-expert field crews could be easily trained to repeat such a measurement. Perhaps the sample technique of visual circle assessments of FWD decayed versus undecayed proportions should be explored. Third, only a limited set of tree species on two sites was explored in this study. Future studies should focus on more diverse tree species in various stages of stand development/disturbance. Finally, there was an indication that a recently harvested site might have substantially more undecayed FWD pieces. Perhaps the stand disturbance/management history collected by FIA field crews could be used as a FWD density reduction factor. More focus could be given to increasing the precision of tallying FWD pieces as opposed to quantifying decay class given the poor repeatability of FWD piece counts (Westfall and Woodall 2007) that might introduce far greater errors in FWD estimates than density assumptions. Overall, given the fractured/decayed state of FWD that is often an ephemeral forest entity, FIA's current methodology of using a mean bulk density for each forest type as the default FWD density appears justified until expanded research indicates a superior methodology.

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Evaluated various techniques for determining the density (i.e., bulk density) of fine woody debris during forest inventory activities. It was found that only experts in dead wood inventory may be able to identify fine woody debris stages of decay. Suggests various future research directions such as development of a 2-class fine woody debris decay class system.

KEY WORDS: detritus, fine woody debris, density, inventory

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