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Sampling Protocol, Estimation, and Analysis Procedures for the Down Woody Materials Indicator of the FIA Program

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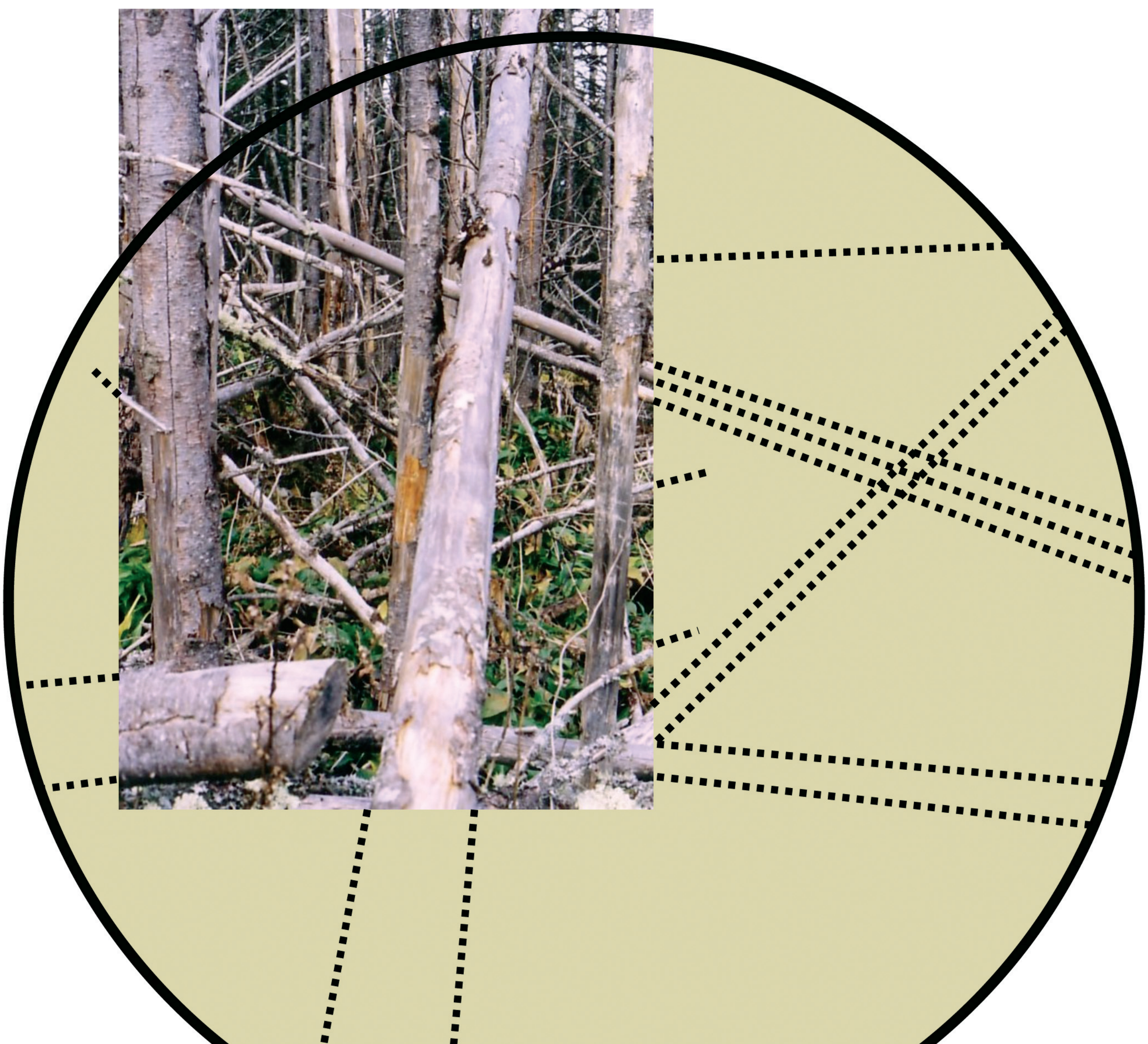

Abstract

The Forest Inventory and Analysis (FIA) program of the USDA Forest Service conducts a national inventory of forests of the United States. A subset of FIA permanent inventory plots are sampled every year for indicators of forest health such as soils, understory vegetation, and down woody materials (DWM). The DWM indicator provides estimates of down and dead woody materials in forest ecosystems. Estimates of DWM are used in assessments of forest-ecosystem attributes such as fuel loadings, carbon stocks, and structural diversity. As defined by the FIA program, DWM comprises fine and coarse woody debris, slash piles, duff, litter, and shrub/herbs cover and height. Components of DWM are sampled using the line-intersect method, point sampling, and fixed-radius sampling. DWM data analyses are an integral part of national inventory reports, multi-scale forest-health reports, and wildlife-habitat, and fuel-loading assessments. The DWM inventory began in 2001 and currently is implemented in 46 states and two territories. In this report we provide the rationale and context for a national inventory of DWM, describe woody material components sampled by the DWM indicator, discuss the sampling protocol used to measure the DWM components and corresponding estimation procedures, and provide guidance on managing and processing DWM data and incorporating that information into pertinent inventory analyses and research projects.

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Foreword

A previous publication by Woodall and Williams (2005), “Sampling, estimation, and analysis procedures for the down woody materials indicator” (Gen. Tech. Rep. NC-256) did not explicitly describe procedures for estimating DWM currently used by the national inventory program. This publication includes these procedures, supporting materials, and refined analytical examples. Finally, this edition has been blind peer-reviewed.

Contents

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1.0 INDICATOR OVERVIEW

1.1 FIA Inventory and Forest-Health Indicators

Forest ecosystems are more than assemblages of trees. They often are associations of flora (e.g., trees, shrubs, herbs, and mosses), fauna (e.g., mammals, amphibians, and soil microbes), and abiotic entities (e.g., decaying organic material, mineral soil, and water). In recognition of this fact, the Forest Inventory and Analysis (FIA) program of the USDA Forest Service conducts an inventory of the Nation's forest ecosystems not only measuring tree components, but also numerous nontimber ecosystem attributes (Gillespie 1999, McRoberts et al. 2004, USDA For. Serv. 1999). Estimating a variety of forest ecosystem attributes, rather than focusing solely on live trees, may better indicate the status and trends in forest-health. The nontimber ecosystem attributes estimated by FIA are collectively referred to as forest-health indicators and currently include tree damage, crown conditions, ozone injury, lichen communities, down woody materials (DWM), vegetation structure and diversity, and soil conditions (McRoberts et al. 2004).

The DWM indicator is sampled in conjunction with FIA's national sampling protocol and occurs on a subset of FIA's regular forest inventory plots. The sampling protocol for all phases of inventory except forest health indicators is described in Bechtold and Patterson (2005). Briefly, FIA's national program consists of three phases of data collection (these phases are not equivalent to three-phase sampling, see Cochran 1977, Chapter 12). During phase 1, auxiliary information is collected to poststratify forest inventory ground plots into a minimum of two strata: forest and nonforest. Stratification can be based on "wall to wall" satellite imagery, which divides the region of interest into strata of known area, or on a dense sample of photo plots that allows estimates of stratum size. Stratified estimation is used in the former case and double sampling for stratification in the latter (Scott et al. 2005). This stratification of inventory sample plots is used to improve the precision of estimates of population totals.

In phase 2 of the FIA inventory, information is gathered from a network of permanent ground plots, with a spatial sampling intensity of approximately one plot per 6,000 acres (Fig. 1.1). Each phase 2 plot consists of four, 24-foot, fixed-radius subplots arranged in a clustered formation (Fig. 1.2). On each subplot, stand and site information such as standing live/dead tree height/diameter and physiographic class/ownership is collected. In special situations, the sample intensity of phase 2 plots can be increased (e.g., one plot per 2,000 acres). Examples of such situations include widespread disturbance events (e.g., hurricanes) or when additional inventory funding is obtained. Standing live and standing dead trees (snags) are inventoried on phase 2 plots; DWM are inventoried during phase 3 of the inventory.

Phase 3, the final phase of the FIA inventory, entails sampling forest-health indicators such as DWM. The DWM sampling protocol is applied to a subset of phase 2 plots (approximately 1/16 of all phase 2 plots, one plot per 96,000 acres) (Fig. 1.1). The first two phases of the FIA sampling

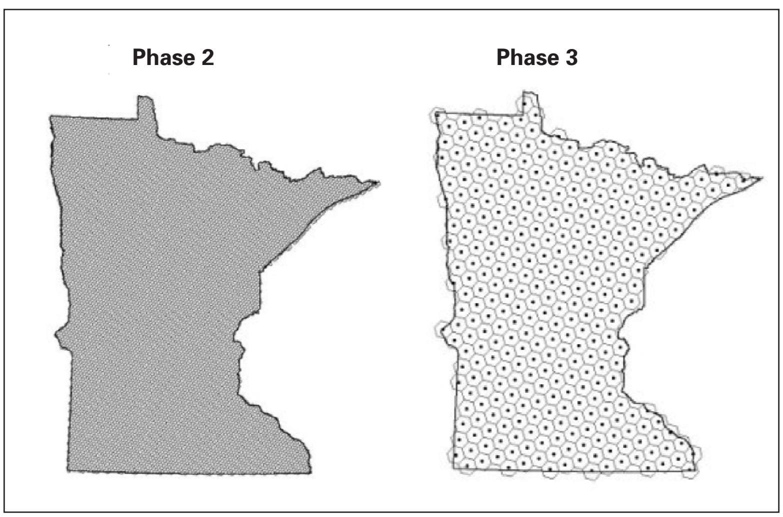


Figure. 1.1. – Approximate hexagonal panel grid for FIA phase 2 (6,000 acre hexagons) and phase 3 (96,000 acre hexagons) inventories in Minnesota.

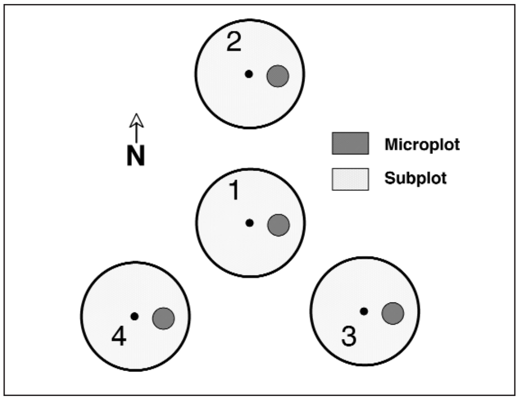


Figure 1.2. – FIA phase 2 sampling design. Each subplot has a fixed radius of 24 feet, with the centers of three subplots arranged around the center of one subplot at a distance of 120 feet at azimuths of 0, 120, and 240, respectively. The microplot is a 6.8-foot fixed-radius plot located 12 feet from each subplot center at a 90-degree azimuth.

protocol are detailed in Bechtold and Patterson (2005); separate sampling design and estimation documents for each indicator collectively describe the third inventory phase (see O'Neill et al. 2005 for soils example). In this publication we describe sampling protocol and estimation procedures for the DWM indicator in the context of FIA's national sampling protocol.

1.2 Down Woody Materials Indicator

The DWM indicator estimates dead organic materials (resulting from plant mortality and leaf turnover) and fuel complexes of live shrubs and herbs. Specifically, components estimated by the DWM indicator are downed fine woody debris (FWD), downed coarse woody debris (CWD), litter, duff, fuelbed, slash piles, live/dead shrubs, and live/dead herbs. Definitions, sample designs, and estimation procedures for each DWM component are included in subsequent sections.

1.2.1 Fire, Wildlife, and Carbon Modeling Sciences

DWM data can be used by scientists – foresters, wildlife biologists, ecologists, fuel specialists, and carbon/climate-change modelers – to quantify the carbon pools, fuels, structure, and wildlife habitat within the Nation's forest ecosystem. Such information also benefits policymakers, state officials, and interested citizens.

The FWD and CWD components of the DWM indicator were designed to match the components defined by the National Fire Danger Rating System (Burgan 1988, Deeming et al. 1979). This system divides FWD and CWD into size classes that are equivalent to the lag-time fuel-class system (1, 10, 100, and 1,000+ hours) used by many fire scientists (Table 1.1). Additionally, litter and duff depths are sampled for estimates of forest floor fuel loadings, and estimates of microplot shrub/herb heights and coverage provide information on forest ladder fuels. Estimates of dead and down woody material, duff/litter, and shrub/herb fuel ladders are integral to numerous fire behavior models (see Albini 1976, Burgan and Rothermal 1984; Finney 1998; Reinhardt et al. 1997, and Rothermal 1972). Along with the entire FIA inventory, the DWM inventory can be used to estimate fuel loads and fire dangers at strategic scales across the United States (Woodall et al. 2005).

The United States, mirroring efforts by other countries (Woldendorp et al. 2002, Kukeuv et al. 1997, Fridman and Walheim 2000), is attempting to quantify forest-ecosystem carbon pools (criterion 5, criteria and indicators for the conservation and sustainable management of temperate and boreal forest; United Nations Framework Convention on Climate Change) (J. For. 1995, Can. For. Serv. 1997, McRoberts et al. 2004). This quantification of the carbon budget can aid in understanding climate change and the role of forest-carbon dynamics in climate-change scenarios. The DWM indicator will increase the

Table 1.1. – Transect diameters (inches) of fine woody debris and their relation to timelag fuel-hour classes

Transect diameter	DWM class	Fuel-hour class
0.00-0.24	Small FWD	1 hr
0.25-0.99	Medium FWD	10 hr
1.00-2.99	Large FWD	100 hr
3.00+	CWD	1,000+ hr

accuracy of estimates of carbon stock across the United States. Estimates of DWM components, such as FWD and CWD, can be coupled with phase 3 estimates of soil organic carbon content and phase 2 estimates of standing tree carbon to create comprehensive carbon estimates in forest ecosystems (O'Neill et al. 2005a, O'Neill et al. 2005b). The FIA program, with all phases contributing toward a comprehensive assessment of total forest carbon, maintains the only national public database for estimating and providing continuous monitoring of forest carbon pools in the United States (Heath and Birdsey 1997).

DWM components such as CWD serve as critical habitat for numerous flora and fauna. From "nurse logs" in the Pacific Northwest to black bear dens in the Southeast, many species find their ecological niche in the shelter of DWM. Flora use the microclimate of moisture, shade, and nutrients provided by CWD to establish regeneration (Harmon et al. 1986). CWD provides structural 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). Due to the possibility of dwindling habitat for many native species across the Nation, inventories of DWM are important for habitat assessments and wildlife conservation (see Ohmann and Waddell 2002, Tietje et al. 2002).

1.2.2 Detection and Evaluation Monitoring

Besides providing estimates and associated variances for DWM components at various spatial scales, the DWM indicator serves in the broader context as a monitoring tool of forest ecosystem health. Data from other phases and forest-health indicators of the FIA program have been used to evaluate the annual status and changes in forest health conditions across all ownerships (Keyes et al. 2003, Woodall et al. 2005). Forest-heath monitoring typically entails detection, evaluation, and intensive site monitoring (Keyes et al. 2003). The baseline down woody inventory provided by the DWM indicator can be used to detect regional disparities in wildlife habitats or prominent fire hazards. Once possible forest-health hazards are detected, these areas can be further evaluated with additional phase 3 plots (plot intensification) or through additional studies (intensive site monitoring) (Tkacz 2002). For example, through analysis of baseline DWM inventory for Minnesota, it might be observed that fuel loadings for the Boundary Waters Canoe Area are relatively high compared to that for the entire Great Lakes region (e.g., Fig. 1.3). Because this might constitute a forest-health hazard, phase 3 plots might be intensified to refine both fuel-loading estimates and mapping.

1.2.3 Current and Expected Outputs

DWM play a varied role in many ecosystem processes. As such, data analysis varies according to the specific issue being addressed. The DWM inventory can be used to address the following primary issues:

- Estimation of DWM attributes per unit area for individual plots. These values can be mapped to determine spatial patterns in DWM, linked to standing live-tree data for modeling efforts, or monitored over time to indicate changes in the DWM resource.

- Estimation of population totals, means, and ratios of DWM attributes, which, in turn, can be used for regional/national DWM assessments.

Estimation techniques for classifying plots and estimating population parameters are based on the same general principles. However, the techniques differ when specific subpopulations are estimated. FIA recognizes two types of subpopulations (*domains*) depending on whether membership is determined by characteristics of the individual piece of DWM or characteristics of the land on which the piece is located. Examples of domains determined by the status and/or attributes of individual pieces of DWM include species, decay status, or piece size. *Condition class* is used to denote area-based subpopulations that can be mapped on the ground (e.g., forest type or ownership).

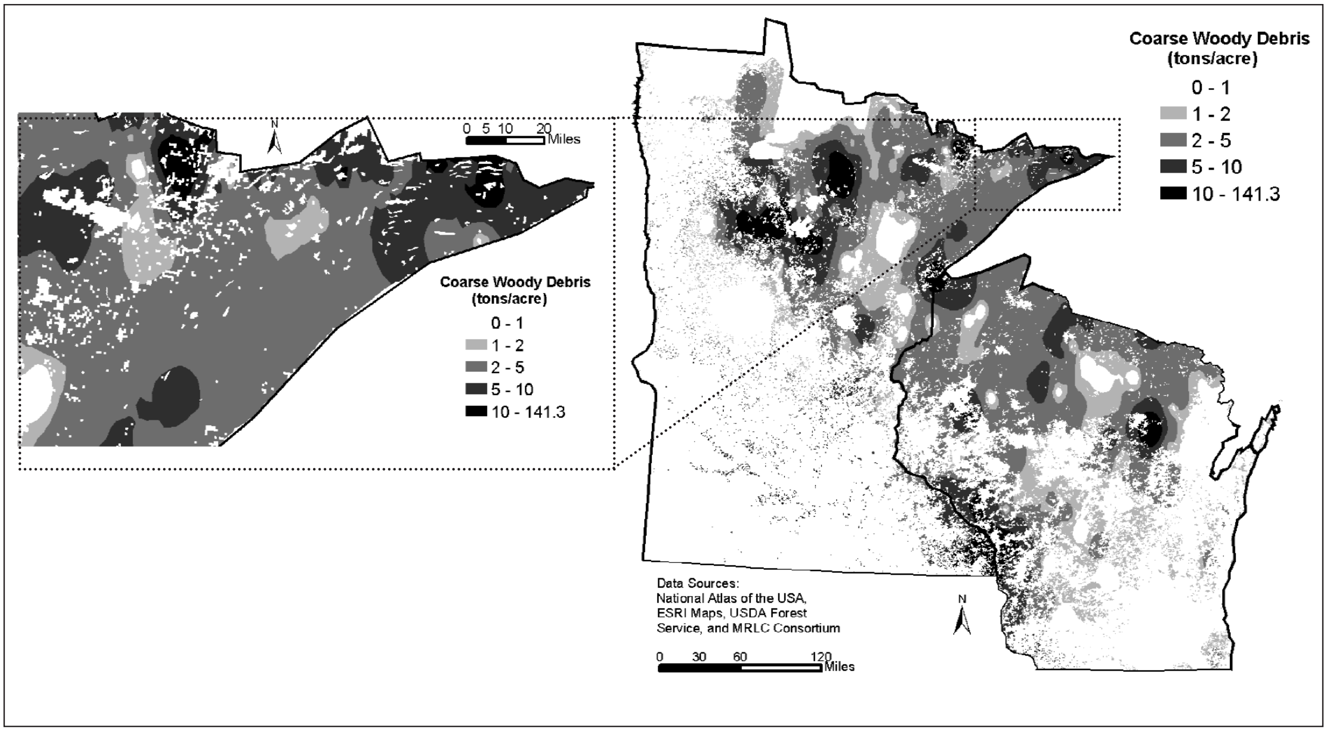


Figure 1.3. – Spatial interpolation of coarse woody debris fuel loadings (tons/acre) for forests in northern Minnesota based on FIA DWM plots, 2001-2003.

Current outputs from the DWM indicator can be grouped into the following categories: field data, core tables, graphical summaries of population estimates, and maps. Field data are organized into tables according to the DWM component (e.g., FWD or CWD) and the sampling protocol that facilitates its estimation. The six tables containing DWM field data are coarse woody debris (Table 1.2), fine woody debris (Table 1.3), duff/litter (Table 1.4), transect (Table 1.5), piles (Table 1.6), and shrub/herbs (Table 1.7). See USDA For. Serv. (2007) for additional information on the preceding tables.

FIA uses the term core tables to refer to standard tabular summaries of inventory data. For phase 2, core tables typically consist of total amounts or estimates per unit area of standing timber volume and number of trees (e.g., total sawtimber volumes on timberland by county for a particular state). Thus, DWM core tables include population-level estimates of totals (e.g., total tons of FWD in the state of Maine) or ratios (e.g., mean 100-hr fuel loading per acre of loblolly pine forest types in South Carolina) for example, see Table 1.8.

Graphical summaries of core tables or population estimates provide more user-friendly outputs for interpreting DWM estimates. Because the phase 3 inventory typically has sample intensities less than that of the phase 2 inventory, analysts should be more cognizant of couching interpretation of DWM estimates in terms of associated sampling errors (Fig. 1.4). The DWM indicator uses a sampling intensity sufficient to indicate the current status and trends in DWM components across large regions of the United States. However, care should be taken when interpreting DWM estimates at smaller scales.

Maps of DWM component estimates allow analysts to estimate not only the amount but also the spatial distribution of DWM components across forest landscapes, for example, forest duff mass across the Upper Midwest. DWM maps may be created through full analytical integration of all three phases of the FIA inventory. Due to the relative low sample intensity of the DWM indicator, modeling efforts often are associated with phase 2 plots and with remotely sensed imagery (Woodall et al. 2004).

To enable analysts to fully utilize DWM data/estimates, research is under way to develop new mapping methodologies, more sophisticated data processing algorithms, seamless integration with other FIA inventory phases, and integration into state/regional reports.

Table 1.2. – FIA coarse woody debris (CWD) field data table with example data

Plot	**Subplot**	**Transect**	**Slope distance**	**Species**	**Transect diameter**	**Small diameter**	**Large diameter**	**Piece length**	**Decay class**	**Hollow**	**CWD History**
xxxx	*x*	*xxx*	*xxx.y (ft)*	*xxx*	*xxx (in)*	*xxx (in)*	*xxx (in)*	*xxx (ft)*	*x*	*x*	*x*
1	1	030	3.5	317	3	3	5	6	2	N	1
1	1	030	4.0	316	11	5	12	22	3	N	1
1	2	030	22.7	316	7	5	8	19	4	N	1
1	3	150	11.1	317	5	4	5	12	1	N	1
1	3	150	2.2	802	9	7	11	37	3	N	1
1	3	270	7.0	316	7			28	5		
1	3	270	15.6	802	3	3	4	24	2	N	1
1	4	270	21.0	802	17	15	18	57	3	Y	1
1	4	270	2.9	202	7	5	7	42	2	N	1

Table 1.3. – FIA's fine woody debris (FWD) field data table with example data

Plot	**Subplot**	**Condition class**	**FWD**			**Reason high**	**Residue pile**
			Small	**Medium**	**Large**		
xxxx	*x*	*x*	*xxx*	*xxx*	*xxx*	*x*	*x*
1	1	1	0	0	2	0	0
1	2	1	8	6	3	0	0
1	3	2	3	1	1	0	0
1	4	1	0	3	1	0	0

Table 1.4. – FIA's duff, litter, and fuelbed field data table with example data

Plot	**Subplot**	**Transect**	**Sample taken**	**Duff depth**	**Litter depth**	**Fuelbed depth**
xxxx	*x*	*xxx*	*x*	*xx.y (in)*	*xx.y (in)*	*xx.y (ft)*
1	1	30	Y	0.2	0.9	2.2
1	1	150	Y	0.8	1.9	4.5
1	1	270	N	0	0	0
1	2	30	Y	0.2	2.0	1.9
1	2	150	Y	1.1	1.7	1.0
1	2	270	Y	0.5	0.8	0.5

Table 1.5. – FIA's transect field data collection table with example data, 2002 to present

Plot	**Subplot**	**Transect**	**Cond. Class**	**Slope Pct**	**Distance** xxx.y (ft)		
xxxx	x	xxx	x	xxx (%)	**Begin slope**	**End slope**	**Horizontal**
1	1	30	1	10	0.0	24.1	24.0
1	1	150	1	5	0.0	24.0	24.0
1	1	270	1	0	0.0	24.0	24.0
1	2	30	1	0	0.0	24.0	24.0
1	2	150	1	0	0.0	24.0	24.0
1	2	270	1	0	0.0	24.0	24.0
1	3	30	2	5	0.0	24.0	24.0
1	3	150	2	0	0.0	24.0	24.0
1	3	270	2	0	0.0	11.5	11.5
1	3	270	1	0	11.6	24.0	12.5
1	4	30	1	10	0.0	24.1	24.0
1	4	150	1	15	0.0	24.3	24.0
1	4	270	1	10	0.0	24.1	24.0

Table 1.6. – FIA's slash/residue pile field data table with example data

Plot	**Subplot**	**Condition class**	**Azimuth**	**Shape**	**Length1**	**Length2**	**Width1**	**Width2**	**Height1**	**Height2**	**Density**
xxxx	*x*	*x*	*xxx (°)*	*x*	*xx (ft)*	*xx (ft)*	*xx (ft)*	*xx (ft)*	*xx (ft)*	*xx (ft)*	*xx (%)*
15	3	1	112	1			9		16		10
27	3	2	127	2	10		11		7		20
35	4	1	50	3	14		4	10	3	6	20
45	1	1	15	3	20		9	15	2	5	30
46	3	3	30	2	21		8		5		10

Table 1.7. – FIA's microplot fuel loading (shrubs and herbs) field data table

Plot	**Subplot**	**Live shrub cover**	**Live shrub HT**	**Dead shrub cover**	**Dead shrub HT**	**Live herb cover**	**Live herb HT**	**Dead herb cover**	**Dead herb HT**	**Litter cover**
xxxx	*x*	*xx (%)*	*xx.y (ft)*	*xx (%)*	*xx.y (ft)*	*xx (%)*	*xx.y (ft)*	*xx (%)*	*xx.y (ft)*	*xx (%)*
1	1	30	6.1	0	0.0	60	1.2	1	1.2	60
1	2	60	5.7	0	0.0	30	1.9	0	0.0	30
1	3	40	4.0	1	3.1	20	1.5	0	0.0	80
1	4	0	6.3	0	0.0	1	2.0	0	0.0	100

Note: HT=tallest height

Table 1.8 – Mean fuel loadings by forest type group and fuel class on forest land (tons/acre), State X, Year 1 to Year 2

Forest-type group	**Down and dead woody fuels**				**Slash**	**Forest floor fuels**	
	1 hr	**10 hr**	**100 hr**	**1000+ hr**		**Duff**	**Litter**
Maple/beech/birch	1.11	2.45	4.44	6.72	2.22	12.22	3.55
Oak/hickory	2.02	4.32	4.21	5.34	4.21	8.84	3.67
Oak/pine	1.97	3.44	5.69	7.54	0.00	13.54	2.64
Elm/ash/cottonwood	3.12	2.17	4.87	8.54	4.87	18.21	5.24
Loblolly/shortleaf pine	1.25	4.11	3.61	6.89	3.61	9.87	2.33
White/red/jack pine	2.33	3.21	5.21	12.11	0.00	11.46	1.34
Other groups	2.22	3.34	3.33	10.54	3.33	7.78	2.43
All forest-type groups	2.33	3.21	5.21	12.11	3.33	11.46	1.34

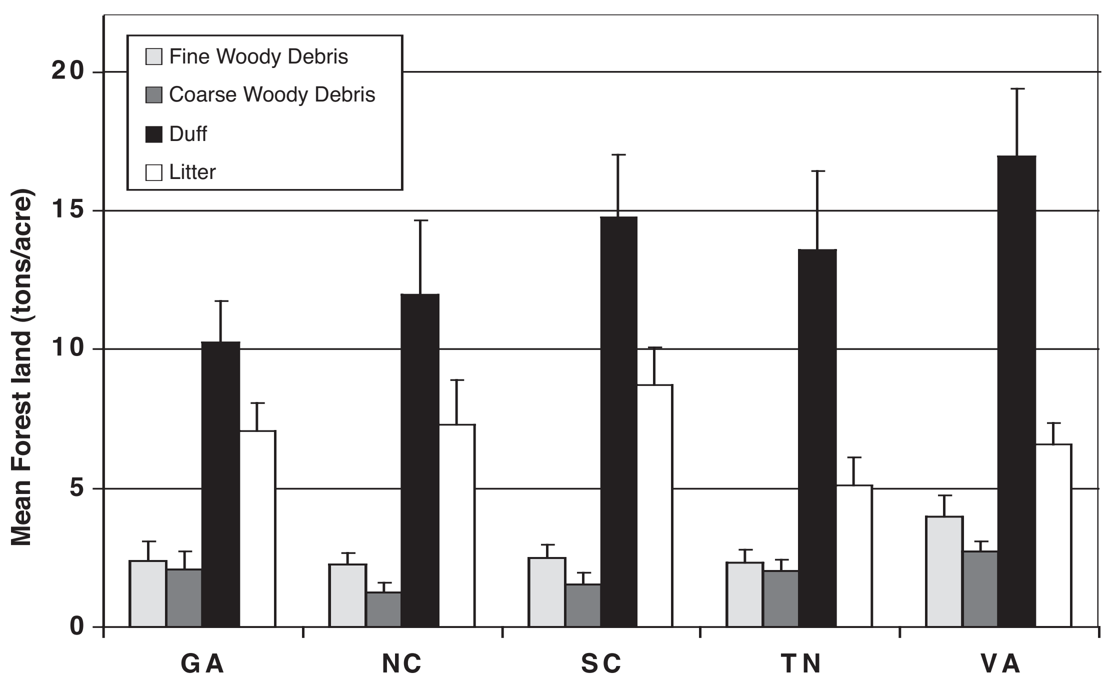


Figure 1.4. – Population estimates of DWM component data for selected states.

2.0 PLOT-BASED SAMPLING PROTOCOL

In this section we present an overview of field protocols for the DWM indicator as currently implemented by FIA. For a detailed description of the protocols implemented by field crews, see USDA For. Serv. (2004) and Appendix 7.6 (field datasheet). The DWM protocols described here have been used by FIA since 2002. For information on historical DWM sample designs used by the Forest Health Monitoring (1999-2000) and the FIA programs (2001), see Appendix 7.5. The Pacific Coast states began sampling CWD in the 1990s (Waddell 2002). For information on organizing field data into a database structure and definitions see USDA For. Serv. (2007). The DWM protocols share components and measurements with phase 2 plots (Bechtold and Patterson 2005).

The diversity of ecosystem attributes estimated by the DWM indicator requires a variety of sampling techniques (Fig. 2.1). FIA field crews cannot efficiently count the number of pine needles, down twigs, and measure the duff depth across an entire plot. Hence, the DWM sampling protocol is distinctly different from phase 2 sampling techniques used to estimate populations of standing trees. The sampling protocol for DWM components includes:

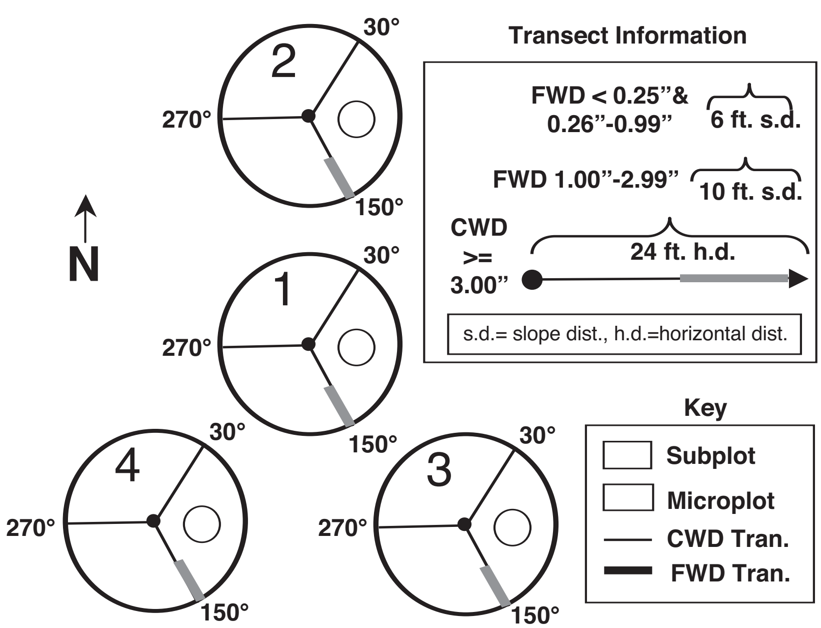
1. Line-intersect sampling for CWD and FWD.

2. Systematic point sampling for duff, litter, and fuelbed depths.

3. Fixed-area plot sampling for cover and height of shrubs and herbs.

4. Fixed-area plot sampling, with shape and packing ratio estimation, for slash/residue piles.

As numerous ecological disciplines may have different definitions for forest ecosystem components sampled by the DWM indicator,



Distance between subplots (2, 3, and 4) and subplot center (1): 120 ft. at angles (deg.) 0, 120, and 240 respectively, distance between subplot center and microplot center: 12 ft.; shrubs/herbs sampled on microplot. Duff/litter sampled at 24-ft. slope distance on each CWD transect.

Figure 2.1. – DWM indicator sampling design on FIA plot (inventory years 2002 to present).

the indicator includes a population definition for each component. As a result, users are cautioned to be fully aware of DWM component definitions that may differ from those used in other disciplines/studies.

2.1 Coarse Woody Debris

FIA considers CWD as dead and downed pieces or portion of pieces of wood that meet the following criteria:

1. Diameter of at least 3 inches along a length of at least 3 feet for decay classes 1-4, and at least 5 inches above the duff layer along a length of at least 5 feet for decay class 5.

2. Detached from the bole of a standing live/dead tree. If still partially rooted, the lean angle must be more than 45 degrees from vertical. Standing dead trees with a lean angle less than 45 degrees from vertical are tallied as snags during the phase 2 inventory.

3. Branched and forked pieces are separated into individual CWD pieces and tallied accordingly. For each piece, a main bole is determined as the fork with the largest diameter, with all branches and secondary forks considered separate CWD pieces that must meet minimum size specifications.

4. If CWD pieces become fractured, whether lengthwise or in broken sections, each portion is treated as a separate piece.

CWD pieces are selected into the sample if the piece's centerline intersects any of three 24-foot horizontal distance transects emanating from the center of each FIA subplot (azimuths of 30, 150, and 270 degrees) (Fig. 2.1). CWD pieces are tallied with each transect intersection as many times as intersected, regardless of the number of intersections. The decay class of each CWD piece is rated according to a 5-class scale (Maser et al. 1979, Sollins 1982) (Table 2.1). Information on decay class allows the determination of mass and habitat condition for CWD pieces. Recorded for pieces in decay classes 1-4 are the slope distance to subplot center, diameter at the point of transect intersection, large-end diameter, small-end diameter (or the minimum 3 inches, whichever is greater), species, decay class, length between the large- and small-end diameters, presence/absence of butt-end cavity, and history. Due to the highly decayed state of class 5, only slope distance, transect diameter, total length

Table 2.1. – Attributes of coarse woody debris pieces used in determining decay classes

Decay class	Structural integrity	Texture of rotten portions	Color of wood	Invading roots	Branches and twigs
1	Sound, freshly fallen, intact logs	Intact, no rot; conks of stem; decay absent	Original color	Absent	Branches are present, fine twigs still are attached and have tight bark.
2	Sound	Mostly intact; soft (starting to decay) but cannot be pulled apart by hand	Original color	Absent	Branches are present, many fine twigs are absent with those remaining have peeling bark
3	Heartwood sound; piece supports its own weight	Hard, large pieces; sapwood can be pulled apart by hand or sapwood absent	Reddish-brown or original color	Sapwood only	Branch stubs will not pull out
4	Heartwood rotten; piece does not support its own weight, but maintains its shape	Soft, small blocky pieces; metal pin can be pushed into heartwood	Reddish or light brown	Throughout	Branch stubs pull out
5	None; piece no longer maintains its shape; it is spread out on the ground	Soft; powdery when dry	Red-brown to dark brown	Throughout	Branch stubs and pitch pockets have usually rotted down

with diameter greater than 5 inches, and decay class are recorded for CWD pieces.

To determine the length of transect in each mapped condition class and attribute estimates of DWM components to condition classes, the beginning and ending distance of each condition class along each CWD transect is recorded. This process is called transect-line segmenting. Rather than calculating horizontal distances in the field, crews record slope distances and the slope of each segment. The condition classes mapped by the DWM indicator match those recorded during phase 2 sampling. Because CWD, FWD, and duff, litter, and fuelbed depth are measured along CWD transects, segmenting on these transects allows estimation of DWM attributes by condition class.

CWD pieces are assigned to a condition class based on the point of intersection between the piece and transect. For pieces that straddle condition classes, the entire length of the piece is measured, rather than only the portion of the length within the mapped condition class. This may result in a slight underestimation when results are reported by condition class for some attributes (when estimators require a measurement of the length of the piece). However, the potential bias is thought to be minimal compared with the errors associated with determining, measuring and recording the length of the piece within each condition class.

2.2 Fine Woody Debris

The DWM indicator defines FWD as down woody pieces with diameter less than 3 inches. In practice, pieces are tallied if the diameter at the point of intersection with the transect is less than 3 inches. FWD does not include dead branches attached to standing trees or shrubs, dead foliage, bark fragments, or small pieces of decomposed wood. Because it would be impractical for field crews to measure the diameter of hundreds of small FWD pieces, they tally the number of FWD pieces by three size classes related to the time-lag fuel classes often referenced by fire scientists (Table 1.1). The three classes of FWD are sampled on each of the four FIA subplots using 6- and 10-foot slope-distance transects collocated on the 150 degree CWD transect and starting at 14-foot slope distance from subplot center (Fig. 2.1). The 6-foot slope distance transect is used to tally the small (0.01 to 0.24 inch) and medium (0.25 to 0.99 inch) classes of FWD; the 10-foot slope-distance transect is used to tally large (1.00 to 2.99 inch) FWD. The slope (percent) of each transect is recorded for use in FWD estimators. If a FWD transect straddles two mapped condition classes, separate tallies are recorded for each condition.

2.3 Duff, Litter, and Fuelbed

The DWM indicator defines litter as a forest-floor layer of freshly fallen leaves, needles, twigs, cones, bark chunks, dead moss, dead lichens, dead herbaceous stems, and flower parts. Duff is defined as an organic forest-floor layer, just below litter, consisting of well decomposed leaves and other organic material. Individual plant parts should not be recognizable in the duff layer. The fuelbed is the accumulated mass of all woody DWM components above the top of the duff layer (excluding live shrubs/herbs). The DWM indicator measures the depth of duff, litter, and fuelbed at 12 points, located at the 24-foot slope distance on each of the 12 CWD transects (Fig. 2.1). If a large obstruction (e.g., boulder or slash pile) is present at the sample locations, crews do not measure duff/litter depths and indicate such in the field data. If the obstruction is a log, only the depth of the fuelbed is measured. Errors in duff, litter, and fuelbed measurements can occur when crews are not trained properly in identifying the duff layer from mineral soils and the litter layer. Crews also must be trained on how to measure the depth of the fuelbed. Fuelbed measurements are not used to estimate fuel loadings (i.e., mass), but to describe the dispersion of fuels from the forest floor up toward the canopy (the fuel complex).

2.4 Fuel Loading on Microplot (Shrubs, Herbs, Litter Cover)

The DWM indicator samples five fuel components on each FIA microplot if its center is an accessible forested condition: dead herbs, live herbs, dead shrubs, live shrubs, and litter coverage (Fig. 2.1). Microplots are 6.8-foot, fixed-radius plots located 12-feet from subplot center at an azimuth of 90 degrees. Within each microplot, the cover and maximum height of each shrub/herb component is estimated visually and recorded. The DWM indicator defines shrubs as vascular plants with woody stems that are not defined as trees by phase 2. Herbs are defined as nonwoody vascular plants including but not limited to ferns, moss, lichens, sedges, and grasses. The cover from 0 to 100 percent in 10-percent classes is estimated for each of the five fuel categories. The tallest height within the microplot of all fuel categories (excluding litter) is also estimated. To produce estimates of mass and/or volume of live/dead shrub/herbs, detailed information on species and form must be collected. Because the vegetation structure and diversity indicator collects this information, the DWM indicator does not collect the data necessary for input to shrub/herb prediction equations. However, data from phase 2 and the vegetation indicator (i.e., shrub species and forest type) can be combined with DWM height/coverage data to estimate shrub/herb volumes/mass (see Brown and Marsden 1976 for an example of calculations of shrub weight).

The entire microplot is assigned to the condition of its center. If a microplot straddles a nonforested condition, fuel loading is determined only in the accessible portion of forest land. If it straddles several forested conditions, one value is recorded for all forested conditions combined. The condition at the center of the microplot is thought sufficient for subsequent estimation, because there is little likelihood of a microplot falling on a condition boundary. Thus, any bias associated with the lack of condition-class mapping on the microplot is thought to be minimal.

2.5 Slash Piles

Slash or residue piles are defined as CWD in piles created directly from human activity or from natural events that prohibit safe measurement by CWD transect. Slash piles are conglomerations of woody debris for which transect sampling would be impractical or hazardous. The sampling protocol for estimating slash pile volume/mass is based on Hardy (1996). A pile is included in the sample if its center is within the accessible forest land area sampled by any FIA subplot (24-foot radius). The shape of each tallied slash pile is classified according to a shape code (Fig. 2.2). Depending on a pile's shape code, certain dimensions of the pile are measured to the nearest foot along with an estimate of the pile's packing ratio. The packing ratio, otherwise termed density, is the ratio of wood volume to total volume within any defined shape. Typically, the packing ratio should not exceed 40 percent. The forest condition class of the center of the slash pile is recorded.

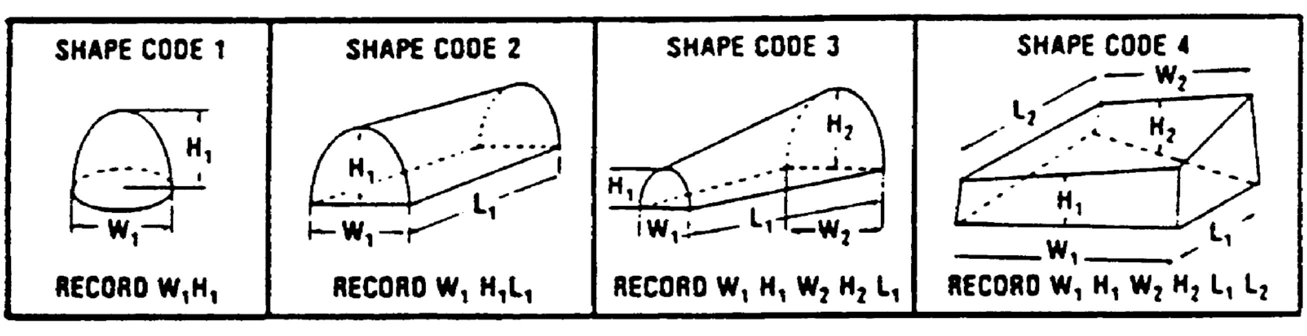


Figure 2.2. – Shape codes for slash/reside piles sampled by FIA.

3.0 ESTIMATING POPULATION ATTRIBUTES

Scott et al. (2005) described general procedures used by FIA to estimate population parameters. In this section, we adapt those principles, methods, and estimators to DWM indicator variables (readers are referred to that publication for additional detail and justification). The components of the DWM indicator are sampled using different protocols. As a result, specific DWM estimators differ substantially from each other and from estimators for attributes of standing trees as described in Scott et al. (2005). However, the general estimation process is the same for all estimators. First, an estimate of the attribute of interest in the domain of interest is computed for each plot and adjusted for plots that overlap the population boundary (section 3.1). Most of the differences in estimation procedures of DWM attributes occur at this step. Second, estimates from all of the plots within a stratum are combined to yield a stratum average and estimated variance (section 3.2). Third, the estimated total for the population is calculated as a weighted average of the strata means using stratum weights (section 3.2). Ratios, such as values per forested acre, are estimated using a ratio-of-means estimator and associated variances (section 3.3). Estimators for individual plots for purposes such as classification, modeling or mapping are described in section 3.4.

Estimation units for phase 2 traditionally have been counties or a combination of counties. However, phase 3 estimation units differ due to different user groups and the less intensive number of sample points per unit area. DWM estimation units may be based on broad ecological classifications, such as Bailey's (1995) ecological provinces and sections, or large administrative or geographic units. Because of the less intensive sample of phase 3 plots, the same strata used for phase 2 estimation may not be appropriate. At a minimum, a forest/nonforest stratification is advisable and currently is used in standard estimation procedures. It should be stressed that users must determine both the appropriate stratification and estimation units for the DWM indicator regardless of what is done for phase 2 estimation. However, a phase 3 stratification can be defined by combining phase 2 strata for a region.

3.1 Computing Attribute of Interest for Each Plot

The first step in estimating population parameters is computing an estimate of the attribute of interest in the domain of interest for each plot. This estimate is corrected for plots that straddle the population boundary. In general, these are plots that straddle international boundaries (Canada or Mexico), are partially left unsampled due to problems related to accessibility (e.g., access denied by owner or hazardous conditions) (see Scott et al. 2005: 48). Nonforested conditions are a domain and part of the population, so they are not included in the correction factor. The computed variables presented here should be considered intermediate steps for obtaining estimates of population totals and averages. To estimate DWM for individual plots or portion of plots for classifying, modeling or mapping, use the estimators described in section 3.4.

3.1.1 Coarse Woody Debris

In each plot, CWD is measured along twelve, 24-foot-long transects. The theory behind line-intersect sampling (LIS) for segmented transects and logs of arbitrary shape is discussed in Appendix 7.1. The LIS estimator is computed for each straight-line transect and then averaged over the three transects per subplot and four subplots per plot (Appendix 7.1.4). From equation 7.10 in Appendix 7.1, the LIS estimator for an attribute of interest in domain of interest d for plot i assigned to stratum h, on a per-unit-area basis, is:

$$y_{hid} = \frac{c(\pi/2)}{12L\overline{p}_h^{CWD}} \sum_{j=1}^{4} \sum_{m=1}^{3} \sum_{t} \frac{y_{hijmt}\delta_{hijmtd}}{l_{hijmt}} \tag{3.1}$$

where

y_{hijmt} is the attribute of interest measured in piece *t* intersected by transect *m* of subplot *j* of plot *i* assigned to stratum *h*. Recall that a piece is recorded as many times as interested by the transect.

l_{hijmt} (ft) is the length of piece *t* intersected by transect *m* of subplot *j* of plot *i* assigned to stratum *h*.

δ_{hijmtd} domain indicator variable which is 1 if piece *t* intersected by transect *m* of subplot *j* of plot *i* assigned to stratum *h* belongs to the domain of interest *d* and 0 otherwise.

L (ft) length of the transect, 24 ft. Because there are 12 transects per plot, the total length is 12 *L*.

c constant to convert to proper units

$\overline{p}_h^{CWD}$ mean proportion of stratum *h* observed transect lengths falling within the population. Dividing by $\overline{p}_h$ adjusts the length of the transect to account for any portion of stratum *h* plots falling outside the population (Scott et al. 2005: 48). This correction factor is simply the ratio of the total length of transect segments actually observed $\left(\sum_{i=1}^{n_h} \sum_{j=1}^{4} \sum_{m=1}^{3} \sum_{k=1}^{K_{hijm}} L_{hijmk}\delta_{hijmk}\right)$ to the length that would had been observed if all plots had fallen entirely within the population ($12Ln_h$):

$$\overline{p}_h^{CWD} = \frac{1}{12Ln_h} \sum_{i=1}^{n_h} \sum_{j=1}^{4} \sum_{m=1}^{3} \sum_{k=1}^{K_{hijm}} L_{hijmk}\delta_{hijmk} \tag{3.2}$$

where

L_{hijmk} (ft) is the horizontal length of the transect segment within condition class *k* on transect *m* of subplot *j* of plot *i* assigned to stratum *h*.

δ_{hijmk} indicator variable which is 1 if condition *k* on transect *m* of subplot *j* of plot *i* assigned to stratum *h* is within the boundaries of the population.

n_h number of phase 3 plots in stratum *h*. Plots that are entirely nonsampled are excluded.

K_{hijm} number of conditions intersected by transect *m* of subplot *j* of plot *i* assigned to stratum *h*.

The attribute of interest in eq. 3.1, y_{hijmt}, could be any attribute measured or calculated in each piece. Table 3.1 includes some of the attributes that can be calculated from FIA data and the corresponding LIS estimator equations. For volume estimation, eq. 3.1 requires an estimate of the volume of each piece. Currently, FIA uses Smalian's formula to calculate the volume of pieces in decay classes 1-4 and

Table 3.1. – Equations for estimating attributes of coarse woody debris from FIA data (Eq. 3.1)

Eq.	Attribute	Units	Equation for the piece (y_{hijmt})	Equation for the plot on a per-unit-area basis (y_{hid})	Comment
1	Volume (Smalian)	ft³/acre	$\frac{(\pi/8)\left(DS_{hijmt}^2 + DL_{hijmt}^2\right)l_{hijmt}}{144}$, (ft³)	$\frac{43560}{144}\left[\frac{(\pi^2/16)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}\left(DS_{hijmt}^2 + DL_{hijmt}^2\right)\delta_{hijmtd}\right]$	Used with pieces in decay classes 1- 4. Volume from Smalian's formula (Husch et al. 1972: 101).
2	Volume (from intercept diameter)	ft³/acre	$\frac{(\pi/4)DI_{hijmt}^2 l_{hijmt}}{144}$, (ft³)	$\frac{43560}{144}\left[\frac{(\pi^2/8)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}DI_{hijmt}^2\delta_{hijmtd}\right]$	Used with pieces in decay class 5
3	Biomass (Smalian)	tons/acre	$BD_{hijmt}DC_{hijmt}V_{hijmt}$, (lb)	$\left(\frac{43560}{144}\right)\left(\frac{1}{2000}\right)\left[\frac{(\pi^2/16)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}BD_{hijmt}DC_{hijmt}\left(DS_{hijmt}^2 + DL_{hijmt}^2\right)\delta_{hijmtd}\right]$	Decay classes 1- 4. V_{hijmt} is Smalian's volume (eq. 1)
4	Biomass (from intercept diameter)	tons/acre	$BD_{hijmt}DC_{hijmt}V_{hijmt}$, (lb)	$\left(\frac{43560}{144}\right)\left(\frac{1}{2000}\right)\left[\frac{(\pi^2/8)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}BD_{hijmt}DC_{hijmt}DI_{hijmt}^2\delta_{hijmtd}\right]$	Decay class 5. V_{hijmt} from eq. 2.
5	Number of pieces	pieces/acre	1, (pieces)	$43560\frac{(\pi/2)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}\frac{\delta_{hijmtd}}{l_{hijmt}}$	
6	Cover (trapezoid)	%	$\frac{\left(DS_{hijmt} + DL_{hijmt}\right)l_{hijmt}/2}{12}$, (ft²)	$\frac{100}{12}\left[\frac{(\pi/2)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}\frac{\left(DS_{hijmt} + DL_{hijmt}\right)\delta_{hijmtd}}{2}\right]$	Assumes that the horizontal projection of the piece is a trapezoid.
7	Cover (from intercept diameter)	%	$\frac{DI_{hijmt}l_{hijmt}}{12}$, (ft²)	$\frac{100}{12}\left[\frac{(\pi/2)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}DI_{hijmt}\delta_{hijmtd}\right]$	

Note: l_{hijmt} (ft), DS_{hijmt} (in), DL_{hijmt} (in), DI_{hijmt} (in), BD_{hijmt} (lb/ft³), and DC_{hijmt} denote the length, small-end diameter, large-end diameter, diameter at the transect intersection point , bulk density (Appendix 7.3), and decay-reduction constant (Table 3.2, Waddell 2002) of piece *t* intersected by transect *m* of subplot *j* of plot *i* assigned to stratum *h*; δ_{hijmtd} is domain indicator variable, it is 1 if piece *t* intersected by transect *m* of subplot *j* of plot *i* assigned to stratum *h* belongs to the domain of interest *d* and 0 otherwise; $\overline{p}_h^{CWD}$ is the mean proportion of stratum *h* observed transect lengths falling within the population (eq. 3.2) and *L* (ft) length of the transect, 24 ft. The decay-reduction constants in Table 3.2 should be used only as defaults when no constants are available for a specific species.

Table 3.2. – Decay-class reduction factors for coarse woody debris by decay class and species group (from Waddell 2002)

Decay class	**Species group**	
	Softwoods	**Hardwoods**
1	1.00	1.00
2	0.84	0.78
3	0.71	0.45
4 and 5	0.45	0.42

the diameter at the intersection for pieces in class 5. Smalian's formula assumes that the shape of the piece is a fustrum of paraboloid and, to the extent that this assumption is not met, a bias will be introduced. Husch et al. (2003:122) and Fraver et al. (2007) reported biases of 12 percent when using Smalian's formula, and the latter examined other formulae that may result in less bias. Alternatively, volume can be estimated from the diameter at the intersection for all pieces. While this method does not require assumptions about the shape of the piece, it is likely to result in greater variance. Since eq. 3.1 can be applied to any method to estimate the volume of individual pieces, users are advised to use the method that they consider most appropriate.

The LIS estimator is derived under the assumption that CWD pieces lie horizontally on the ground. If this is not the case, due to the slope of the terrain or because the piece is partially hanging, the length of each piece in eq. 3.1 must be multiplied by the cosine of the angle between the piece and the horizontal plane. The resulting correction factor ranges from 1 (no correction) for horizontal pieces to a maximum of 1.41 for a 45-degree lean angle. The correction factor always is greater than or equal to 1, so ignoring it results in underestimating the target parameter. For small to moderate piece inclination, the correction factor is relatively small: 1.015 (1.5 percent) for an inclination of 10 degrees and 1.064 (6.4 percent) for an inclination of 20 degrees. FIA does not measure piece inclination and the correction factor is set to 1 by default.

3.1.2 Fine Woody Debris

FWD is measured by tallying the number of pieces in each of three diameter classes within each condition class crossed by the transect. Four transects are measured in each plot, with length varying with the diameter of the pieces. Not recorded are the actual diameter, species, or other attributes of individual pieces. Thus, estimation of FWD is limited to total volume and weight and the only possible domains are those based on mapped condition classes. An additional complication is that the length of the transect is not corrected for slope during field measurements, so slope correction must be incorporated into the FWD estimator.

The LIS estimator of the total volume of fine woody debris (ft^3/acre), for each size class, is obtained from eq. 7.9 in Appendix 7.1:

$$y_{hid} = \frac{43560}{144}\left[\frac{\left(\pi^2/8\right)}{4\bar{p}_h^{FWD}}\sum_{j=1}^{4}\sum_{k=1}^{K_{hij}}\frac{s_{hijk}n_{hijk}\overline{QMDI}^{2}_{hijk}\delta_{hijkd}}{L_{hijk}}\right] \tag{3.3}$$

where

s_{hijk} is the slope correction factor for the segment in condition class k of subplot j of plot i assigned to stratum h :

$$s_{hijk} = \sqrt{1 + \left(\%\ \text{slope}_{hijk} / 100\right)^2} \tag{3.4}$$

L_{hijk} (ft) is the slope-length of the transect segment in condition class k of subplot j of plot i assigned to stratum h.

n_{hijk} is the number of FWD pieces tallied in the diameter class of interest in condition class k of subplot j of plot i assigned to stratum h.

$\overline{QMDI}_{hijk}$ (in) is the quadratic mean diameter of the diameter class of interest in condition class k of subplot j of plot i assigned to stratum h (Appendix 7.4).

δ_{hijkd} domain indicator variable which is 1 if condition class k of subplot j of plot i assigned to stratum h is in the condition classes of interest d and 0 otherwise.

$\overline{p}_h^{FWD}$ mean proportion of stratum h observed transect lengths falling within the population:

$$\overline{p}_h^{FWD} = \frac{1}{4Ln_h} \sum_{i=1}^{n_h} \sum_{j=1}^{4} \sum_{k=1}^{K_{hij}} L_{hijk} \delta_{hijk} \tag{3.5}$$

where

δ_{hijk} indicator variable which is 1 if condition k on transect m of subplot j of plot i assigned to stratum h is within the boundaries of the population.

L (ft) length of the FWD transect: 6 ft for the small (0.01 to 0.24 inch) and medium (0.25 to 0.99 inch) diameter classes and 10 ft for the large (1.00 to 2.99 inches) diameter class.

To estimate biomass, volume estimates are multiplied by the bulk density of FWD and an assumed decay-reduction factor of 0.80 (Appendix 7.4). As with CWD decay reduction factors, if refined FWD decay reduction factors are available for a FWD class and forest-type group, they should be used rather than the default constant. An estimate of the total amount of FWD for the plot can be obtained by computing eq. 3.3 for each diameter class and then adding the three estimates at the plot level.

The FWD estimator is affected by the same problem described for nonhorizontal pieces. However, the underestimation may be much greater for FWD than for CWD. First, the inclination of FWD pieces may be greater that than of CWD pieces, particularly for fresh slash and when FWD is still attached to fallen branches (Brown and Roussopoulos 1974). Second, FWD tilt angle is not limited to a maximum inclination of 45 degrees. Brown and Roussopoulos (1974) examined this issue with a large sample of FWD pieces from conifer forests. The average correction factor for naturally fallen braches ranged between 1.09 and 1.21 depending on forest type and piece size class. For slash, the correction factors were as high as 1.38 for recent slash and 1.25 for older slash. FIA sets the correction factor to 1.13 by default (Brown 1974), but analysts are encouraged to use specific correction factors where available.

The LIS estimator in eq. 3.3 requires measurement of the quadratic mean diameter (QMD) of the pieces tallied. However, FIA tallies only the number of pieces within each class, not individual diameters. In many instances, the midpoint diameter of the size class has been used a surrogate for the QMD. However, the distribution of piece size is not uniform (smaller pieces are more abundant) and the QMD tends to be smaller than the midpoint diameter of the size class. For example, the QMD of a sample of ponderosa pine FWD pieces in the 1- to 3-inch class was 1.77 inches, but the midpoint of the interval is 2 inches (Brown and Roussopoulos 1974). Using 2 rather than 1.77 inches in eq. 3.3 would overestimate the volume of FWD by 28 percent. Several authors have published estimated QMD for selected species or forest types (e.g., Brown and Roussopoulos 1974, Ryan and Pickford 1978, Nalder et al. 1997, 1999), but most regions lack estimates. Van Wagner (1982) proposed a method for estimating QMD without additional field work or the need to identify the species of individual pieces. This method is based on the assumption that the distribution of piece diameters follows a power function. The default QMD values included in Appendix 7.4 are based on this method (Woodall and Monleon, in press).

3.1.3 Duff, Litter, and Fuelbed

Duff, litter, and fuelbed depth are estimated at 12 points per plot, located systematically at the 24-foot slope-distance location on each CWD transect. In addition to average depth, duff and litter mass are calculated. For each attribute, the depth in domain (condition class) of interest d for plot i assigned to stratum h, is:

$$y_{hid} = \frac{\sum_{j=1}^{4}\sum_{m=1}^{3} y_{hijm}\delta_{hijmd}}{12\overline{p}_h^{DLF}} \tag{3.6}$$

where

y_{hijm} (in) is the depth of the duff, litter, or fuelbed at the end of transect m of subplot j of plot i assigned to stratum h.

δ_{hijmd} domain indicator variable which is 1 if the point at the end of transect m of subplot j of plot i assigned to stratum h belongs to the domain of interest d and 0 otherwise.

$\overline{p}_h^{DLF}$ mean proportion of stratum h observed points falling within the population:

$$\overline{p}_h^{DLF} = \sum_{i=1}^{n_h}\sum_{j=1}^{4}\sum_{m=1}^{3}\frac{\delta_{hijm}}{12n_h} \tag{3.7}$$

where

δ_{hijm} domain indicator variable which is 1 if the points at the end of transect m of subplot j of plot i assigned to stratum h is within the boundaries of the population.

To compute litter and duff weights per unit area, the depth (y_{hijm} in eq. 3.6) is multiplied by bulk density (lb/ft^3, Appendix 7.4) and a unit-conversion factor. If the depth is measured in inches, the unit-conversion factor that yields tons per acre is 1.815.

3.1.4 Fuel Loading on Microplot (Shrubs, Herbs, Litter Cover)

The maximum height and total cover of dead and live shrubs and herbs are measured in each of the four microplots. The entire microplot is assigned to the condition class at its center. The height or cover in the domain (condition class) of interest *d* for plot *i* assigned to stratum *h*, is:

$$y_{hid} = \frac{\sum_{j=1}^{4} y_{hij}\delta_{hijd}}{4\overline{p}_h^{FL}} \qquad (3.8)$$

where

y_{hij} is the depth (ft) or cover (expressed as a proportion) of herbs, shrubs, or litter at microplot *j* of plot *i* assigned to stratum *h*.

δ_{hijd} domain indicator variable which is 1 if microplot *j* of plot *i* assigned to stratum *h* belongs to the domain of interest *d* and 0 otherwise.

$\overline{p}_h^{FL}$ mean proportion of stratum h observed microplots falling within the population:

$$\overline{p}_h^{FL} = \sum_{i=1}^{n_h}\sum_{j=1}^{4}\frac{\delta_{hij}}{4n_h} \qquad (3.9)$$

where

δ_{hij} indicator variable which is 1 if microplot *j* of plot *i* assigned to stratum *h* is within the boundaries of the population.

3.1.5 Slash Piles

A slash pile is tallied if its center falls within the subplot boundary. The volume of the pile is determined based on the pile's shape and associated sampled dimensions (Fig 2.2) using equations from Table 3.3.

The weight of an individual pile is estimated by multiplying the pile's net volume by a slash bulk-density constant (Appendix 7.4) and a unit conversion constant (0.0005 to convert to tons). Then, pile volume (ft^3/acre) or weight (tons/acre) in domain of interest *d* for plot *i* assigned to stratum *h*, is:

$$y_{hid} = \frac{\sum_{j=1}^{4}\sum_{t} y_{hijt}\delta_{hijtd}}{4a_{sub}\overline{p}_h^{PILE}} \qquad (3.10)$$

where

y_{hijt} is the volume (ft^3) or weight (tons) of pile *t* in subplot *j* of plot *i* assigned to stratum *h*.

δ_{hijtd} domain indicator variable which is 1 if pile *t* in subplot *j* of plot *i* assigned to stratum *h* belongs to the domain of interest *d* and 0 otherwise.

a_{sub} (acres) area of the subplot (1/24 acre). There are four subplots, so $4a_{sub}$ is the total area sampled in the plot.

Table 3.3. – Equations for determining the net volume of slash piles based on its shape (adapted from Hardy 1996)

Shape code	**Net volume equation**
1 – Paraboloid	$P\pi hw^2/8$
2 – Half-elliptical cylinder	$P\pi hwl/4$
3 – Half-frustum of an elliptical cone	$P\pi l\left(h_1w_1+\sqrt{h_1w_1h_2w_2}+h_2w_2\right)/12$
4 – Irregular solid	$P\left(l_1+l_2\right)\left(w_1+w_2\right)\left(h_1+h_2\right)/8$

Note: *P* is the packing ratio, and *h*, *w* and *l* are size measurements according to the pile's shape code (Fig 2.2).

$\bar{p}_h^{PILE}$ mean proportion of stratum *h* observed plot areas falling within the population:

$$\bar{p}_h^{PILE}=\sum_{i=1}^{n_h}\sum_{j=1}^{4}\sum_{k}^{K_{hij}}\frac{a_{hijk}\delta_{hijk}}{4a_{sub}n_h} \tag{3.11}$$

where

a_{hijk} area of subplot covering condition class *k* on subplot *j* of plot *i* assigned to stratum *h.*

δ_{hijk} domain indicator variable which is 1 if condition *k* on subplot *j* of plot *i* assigned to stratum *h* is within the boundaries of the population.

It should be noted that the biomass of CWD in slash piles can be reduced by incorporating a decay reduction factor, as occurred in the CWD estimator. Because there is no species or decay information for slash piles, the decay reduction factor would implicitly be based on expert opinion. Starting values for slash pile decay reduction factors may be based on forest type and decay classes of 1 or 2.

3.2 Estimating Population Totals and Variances

Once attributes are calculated at the plot level, the estimation of stratum averages and population totals proceeds as described in Scott et al. (2005: 54-55). Those equations are included here for completeness. First, calculated plot values are averaged within each stratum:

$$\bar{Y}_{hd}=\frac{\sum_{i=1}^{n_h}y_{hid}}{n_h} \tag{3.12}$$

where

y_{hid} is the plot estimated value from eqs. 3.1, 3.3, 3.6, 3.8, or 3.10.

n_h is the number of observed plots in the stratum.

The variance estimator of eq. 3.12 is:

$$\operatorname{var}\left(\bar{Y}_{hd}\right)=\frac{\sum_{i=1}^{n_h}\left(y_{hid}-\bar{Y}_{hd}\right)^2}{n_h\left(n_h-1\right)} \tag{3.13}$$

Estimated population totals for the domain of interest are weighted averages of the stratum means multiplied by the total population area. For stratified estimation and double sampling for stratification, respectively, the estimators are

$$\hat{Y}_d = A_T \sum_{h=1}^{H} W_h \bar{Y}_{hd} \tag{3.14}$$

where

A_T (acres) total area of the population.

W_h weight for stratum *h,* calculated as the proportion of the area of stratum *h* to that of the population A_T.

n'_h number of phase 1 plots classified as belonging to stratum *h.*

n' total number of phase 1 plots sampled in the population.

H total number of strata in the population.

For variables such as those involving estimates of depth, height or cover, the population total is not a meaningful parameter. The parameter of interest typically the mean, which can calculated by dividing equation (3.14) by the total area A_T or, more appropriately, by the forested area or area in the condition class of interest (see ratio estimation, section 3.3).

An approximate variance of the estimated total for stratified sampling and double sampling for stratification, respectively, is given by:

$$\operatorname{var}\left(\hat{Y}_d\right)=\frac{A_T^2}{n}\left[\sum_{h=1}^{H} W_h n_h \operatorname{var}\left(\bar{Y}_{hd}\right)+\sum_{h=1}^{H}\left(1-W_h\right)\frac{n_h}{n}\operatorname{var}\left(\bar{Y}_{hd}\right)\right]$$

$$\operatorname{var}\left(\hat{Y}_d\right)=\frac{A_T^2}{n}\left[\sum_{h=1}^{H}\left(\frac{n'_h-1}{n'-1}\right)\frac{n'_h}{n'}\operatorname{var}\left(\bar{Y}_{hd}\right)+\frac{1}{n'-1}\sum_{h=1}^{H}\frac{n'_h}{n'}\left(\bar{Y}_{hd}-\sum_{h=1}^{H}\frac{n'_h}{n'}\bar{Y}_{hd}\right)^2\right] \tag{3.15}$$

where n is the total number of observed plots, $n = \sum_{h=1}^{H} n_h$.

3.3 Estimating Ratios

In many instances, users are not interested in estimated population totals but in estimates of the attribute expressed on a per-acre or per-piece basis. For example, a user may be interested in the average volume of CWD per acre of ponderosa pine forest, or the per-acre average number of pieces larger than 20 inches in Douglas-fir forests of western Oregon. This is accomplished by dividing an estimate of the total of the attribute in the domain of interest (i.e., total number of CWD pieces greater than 20 inches in Douglas-fir forest of western Oregon) by an estimate of the area covered by the domain of interest (Douglas-fir forest of western Oregon). In general, most attributes are reported in a per-forested-acre basis rather than total area of the population. In such cases a ratio estimator with the estimated number of forested acres in the denominator would be used.

3.3.1 Ratio Estimator

The ratio estimator and its approximate estimated variance are (Scott et al. 2005: 55):

$$\hat{R}_{dd'} = \frac{\hat{Y}_d}{\hat{X}_{d'}} \tag{3.16}$$

where $\hat{Y}_d$ and $\hat{X}_{d'}$ are estimators of the population total for two attributes in the domains of interest *d* and *d'*, respectively. Typically, $\hat{X}_{d'}$ would be an estimator of total area or total number of pieces.

$$\operatorname{var}\left(\hat{R}_{dd'}\right) = \frac{1}{\hat{X}_{d'}^2}\left[\operatorname{var}\left(\hat{Y}_d\right) + \hat{R}_{dd'}^2 \operatorname{var}\left(\hat{X}_{d'}\right) - 2\hat{R}_{dd'} \operatorname{cov}\left(\hat{Y}_d, \hat{X}_{d'}\right)\right] \tag{3.17}$$

For stratified sampling, the covariance is estimated as (terms defined in section 3.2):

$$\operatorname{cov}\left(\hat{Y}_d, \hat{X}_{d'}\right) = \frac{A_T}{n}\left[\sum_{h=1}^{H} W_h n_h \operatorname{cov}\left(\overline{Y}_{hd}, \overline{X}_{hd'}\right) + \sum_{h=1}^{H}\left(1 - W_h\right)\frac{n_h}{n}\operatorname{cov}\left(\overline{Y}_{hd}, \overline{X}_{hd'}\right)\right] \tag{3.18}$$

$$\operatorname{cov}\left(\overline{Y}_{hd}, \overline{X}_{hd'}\right) = \frac{\sum_{i=1}^{n_h} y_{hid} x_{hid'} - n_h \overline{Y}_{hd} \overline{X}_{hd'}}{n_h\left(n_h - 1\right)} \tag{3.19}$$

For double sampling for stratification, the covariance is estimated as:

$$\operatorname{cov}\left(\hat{Y}_d, \hat{X}_{d'}\right) = A_T^2\left[\sum_{h=1}^{H}\left(\frac{n'_h - 1}{n' - 1}\right)\frac{n'_h}{n'}\operatorname{cov}\left(\overline{Y}_{hd}, \overline{X}_{hd'}\right) + \frac{1}{n' - 1}\sum_{h=1}^{H}\frac{n'_h}{n'}\left(\overline{Y}_{hd} - \overline{Y}_d\right)\left(\overline{X}_{hd'} - \overline{X}_{d'}\right)\right] \tag{3.20}$$

$$\operatorname{cov}\left(\overline{Y}_{hd}, \overline{X}_{hd'}\right) = \frac{\sum_{i=1}^{n_h} y_{hid} x_{hid'} - n_h \overline{Y}_{hd} \overline{X}_{hd'}}{n_h\left(n_h - 1\right)} \tag{3.21}$$

3.3.2 Area Estimation

Area estimation per se is not of interest for the DWM indicator. FIA produces area estimates such as the number of acres of forest land from the mapped phase 2 plots. However, for estimating ratios of DWM attributes on a per-acre basis, eq. 3.16 requires an estimator of total area in the domain on interest. For this purpose, area can be estimated in two ways: directly from phase 3 variables, such as the proportion of transect length in the domain of interest, or from the proportion of the mapped plot area in the domain of interest. Estimates calculated directly from phase 3 variables may be advantageous. First, the covariance between the estimator of the attribute of interest and the estimator of area may be greater if area is estimated from the DWM indicator data than from mapped data. As a result, the variance of the ratio estimator (eq. 3.17) may be reduced. Second, estimating both the numerator and denominator from DWM indicator data may simplify calculations since extraneous data need not be considered. However, estimating area from the much larger phase 2 sample may result in a more precise estimator of area and, as a result, reduced variance of the ratio estimator. The development of methods that combine phase 2 and 3 data to improve the precision of phase 3 estimation is an active area of research within FIA. Interested users should follow those developments and apply those estimators as they become available.

For each plot, the proportion of the plot in the domain of interest is calculated as:

$$p_{hid} = \frac{1}{12L\overline{p}_h^{CWD}} \sum_{j=1}^{4} \sum_{m=1}^{3} \sum_{k=1}^{K_{hijm}} L_{hijmk} \delta_{hijmkd} \qquad \text{for CWD} \qquad (3.22)$$

$$p_{hid} = \frac{1}{4L\overline{p}_h^{FWD}} \sum_{j=1}^{4} \sum_{k=1}^{K_{hij}} \frac{L_{hijk} \delta_{hijkd}}{s_{hijk}} \qquad \text{for FWD} \qquad (3.23)$$

$$p_{hid} = \frac{1}{12\overline{p}_h^{DLF}} \sum_{j=1}^{4} \sum_{m=1}^{3} \delta_{hijmd} \qquad \text{for duff, litter, and fuelbed measurements} \qquad (3.24)$$

$$p_{hid} = \frac{1}{4\overline{p}_h^{FL}} \sum_{j=1}^{4} \delta_{hijd} \qquad \text{for fuel-loading (shrubs and herbs) variables} \qquad (3.25)$$

$$p_{hid} = \frac{1}{4a_{sub}\overline{p}_h^{PILE}} \sum_{j=1}^{4} \sum_{k}^{K_{hij}} a_{hijk} \delta_{hijkd} \qquad \text{for slash piles} \qquad (3.26)$$

where the indicator variable δ is 1 if the transect segment, point, microplot or plot area is within the condition class of interest and 0 otherwise, and the remaining symbols are described in their respective sections.

The total area in the domain of interest is calculated following the estimators in section 3.2, substituting p_{hid} for y_{hid} in equation 3.12 and 3.13. The estimated total area is then used in the denominator of the ratio estimator (eq. 3.16).

3.4 Estimating DWM for Individual Plots or Portion of Plots

For uses such as modeling, classifying plots, or mapping, it may be of interest to estimate DWM attributes for individual plots or for condition classes within plot. When calculating separate estimates per condition class within a plot, caution should be used when the transect length or number of points in the condition class is small. In this situation, unreliable estimates may result. This situation is relatively rare with FIA data, and the appropriate solution may depend on the intended use. In general, we recommend that the transect length or number of points equivalent to those of an entire subplot should be the minimum for plot-level calculations (Bechtold and Scott 2005: 40).

3.4.1. Coarse Woody Debris

From eq. 7.7 in Appendix 7.1, the LIS estimator for an attribute of interest in domain of interest *d* for a plot, on a per-unit-area basis, can be computed as:

$$y_d = c \frac{\frac{\pi}{2} \sum_{j=1}^{4} \sum_{m=1}^{3} \sum_{t} y_{jmt} \delta_{jmtd} / l_{jmt}}{\sum_{j=1}^{4} \sum_{m=1}^{3} L_{jmd'}} \qquad (3.27)$$

where

y_{jmt} is the attribute of interest measured in piece *t* intersected by transect *m* of subplot *j*. A piece is recorded as many times as intersected by the transect.

l_{jmt} (ft) is the length of piece *t* intersected by transect *m* of subplot *j*.

δ_{jmtd} domain indicator variable which is 1 if piece *t* intersected by transect *m* of subplot *j* belongs to the domain of interest *d* and 0 otherwise.

$L_{jmd'}$ (ft) length of the segment of transect *m* of subplot *j* in the condition class of interest *d'*.

c constant to convert to proper units.

The attribute of interest in equation 3.27, y_{hijmt}, could be any attribute measured or calculated in each piece. Table 3.4 lists some of the attributes that can be calculated from FIA data and the corresponding estimator equations.

3.4.2. Fine Woody Debris

The estimator of the total volume of fine woody debris (ft^3/acre), for each size class, is obtained from eq. 7.9 in Appendix 7.1:

$$y_d = \frac{43560}{144} \left[\frac{\frac{\pi^2}{8} \sum_{j=1}^{4} \sum_{k=1}^{K_j} n_{jk} \overline{QMDI}_{jk}^{2} \delta_{jkd}}{\sum_{j=1}^{4} \left(L_{jd'} / s_{jd'} \right)} \right] \qquad (3.28)$$

where

$L_{jd'}$ (ft) slope-length of the transect segment on subplot *j* in the condition class of interest *d'*.

δ_{jmd} is the slope correction factor for the segment in the condition class of interest *d'* of subplot *j* (eq. 3.4).

n_{jk} is the number of FWD pieces tallied in the diameter class of interest in condition class *k* of subplot *j*.

$\overline{QMDI}_{jk}$ (in) is the quadratic mean diameter of the diameter class of interest in condition class *k* of subplot *j* (Appendix 7.4).

Table 3.4. – Equations to estimate coarse woody debris attributes from individual plots (eq. 3.27)

Eq.	Attribute	Units	Equation for the piece (y_{jmt})	Equation for the plot on per-unit-area basis (y_d)	Comment
1	Volume (Smalian)	ft³/acre	$\frac{(\pi/8)(DS_{jmt}^2 + DL_{jmt}^2)l_{jmt}}{144}$, (ft³)	$\frac{43560}{144}\left[\frac{\frac{\pi^2}{16}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}(DS_{jmt}^2 + DL_{jmt}^2)\delta_{jmtd}}{\sum_{j=1}^{4}\sum_{m=1}^{3}L_{jmd'}}\right]$	Used with pieces in decay class 1- 4. Volume from Smalian's formula (Husch et al. 1972: 101).
2	Volume (from intercept diameter)	ft³/acre	$\frac{(\pi/4)DI_{jmt}^2 l_{jmt}}{144}$, (ft³)	$\frac{43560}{144}\left[\frac{\frac{\pi^2}{8}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}DI_{jmt}^2\delta_{jmtd}}{\sum_{j=1}^{4}\sum_{m=1}^{3}L_{jmd'}}\right]$	Used with pieces in decay class 5
3	Biomass (Smalian)	tons/acre	$BD_{hijmt}DC_{hijmt}V_{hijmt}$, (lb)	$\left(\frac{43560}{144}\right)\left(\frac{1}{2000}\right)\left[\frac{\frac{\pi^2}{16}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}BD_{jmt}DC_{jmt}(DS_{jmt}^2 + DL_{jmt}^2)\delta_{jmtd}}{\sum_{j=1}^{4}\sum_{m=1}^{3}L_{jmd'}}\right]$	Decay classes 1- 4. V_{hijmt} is Smalian's volume (eq. 1)
4	Biomass (from intercept diameter)	tons/acre	$BD_{hijmt}DC_{hijmt}V_{hijmt}$, (lb)	$\left(\frac{43560}{144}\right)\left(\frac{1}{2000}\right)\left[\frac{\frac{\pi^2}{8}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}DB_{jmt}DC_{jmt}DI_{jmt}^2\delta_{jmtd}}{\sum_{j=1}^{4}\sum_{m=1}^{3}L_{jmd'}}\right]$	Decay class 5. V_{hijmt} from eq. 2.
5	Number of pieces	pieces/acre	1, (pieces)	$43560\left[\frac{\frac{\pi}{2}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}\delta_{jmtd}/l_{jmt}}{\sum_{j=1}^{4}\sum_{m=1}^{3}L_{jmd'}}\right]$	
6	Cover (trapezoid)	%	$\frac{(DS_{jmt} + DL_{jmt})l_{jmt}/2}{12}$, (ft²)	$\frac{100}{12}\left[\frac{\frac{\pi}{2}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}(DS_{jmt} + DL_{jmt})\delta_{jmtd}/2}{\sum_{j=1}^{4}\sum_{m=1}^{3}L_{jmd'}}\right]$	Assumes that the horizontal projection of the piece is a trapezoid.
7	Cover (from intercept diameter)	%	$\frac{DI_{jmt}l_{jmt}}{12}$, (ft²)	$\frac{100}{12}\left[\frac{\frac{\pi}{2}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}DI_{jmt}\delta_{jmtd}}{\sum_{j=1}^{4}\sum_{m=1}^{3}L_{jmd'}}\right]$	

Note: l_{jmt} (ft), DS_{jmt} (in), DL_{jmt} (in), DI_{jmt} (in), BD_{jmt} (lb/ft³), and DC_{jmt} denote the length, small-end diameter, large-end diameter, diameter at the transect intersection point , bulk density (Appendix 7.3), and decay-reduction constants (Table 3.2, Waddell 2002) of piece *t* intersected by transect *m* of subplot *j*; δ_{jmtd} is domain indicator variable, it is 1 if piece *t* intersected by transect *m* of subplot *j* belongs to the domain of interest *d* and 0 otherwise; and $L_{jmd'}$ (ft) length of transect *m* of subplot *j* in the condition class of interest *d'*. The decay reduction constants in Table 3.2 should only be used as defaults when no constants are available for a specific species.

δ_{jkd} domain indicator variable which is 1 if condition class *k* of subplot *j* is the condition classes of interest *d* and 0 otherwise.

To compute FWD mass per unit area, the volume of FWD (y_d) must be multiplied by bulk density and the decay-reduction factor as presented in eq. 3.5.

3.4.3 Duff, Litter, and Fuelbed

Duff, litter, and fuelbed depth in domain of interest *d* is:

$$y_d = \frac{\sum_{j=1}^{4}\sum_{m=1}^{3} y_{jm}\delta_{jmd}}{\sum_{j=1}^{4}\sum_{m=1}^{3}\delta_{jmd}} \quad (3.29)$$

where

y_{jm} (in) is the depth of the duff, litter, or fuelbed at the end of transect *m* of subplot *j*.

δ_{jmd} domain indicator variable which is 1 if the point at the end of transect m of subplot *j* belongs to the condition class of interest *d* and 0 otherwise.

To compute litter and duff mass per unit area, the depth (y_{jm} in eq. 3.29) is multiplied by bulk density (Appendix 7.4) and a unit-conversion factor. If the depth is measured in inches, the unit-conversion factor to obtain tons per acre is 1.815.

3.4.4 Fuel Loading (Shrubs, Herbs, and Litter Cover)

The average maximum height and cover of dead and live shrubs, herbs in the domain of interest *d,* is:

$$y_d = \frac{\sum_{j=1}^{4} y_j\delta_{jd}}{\sum_{j=1}^{4}\delta_{jd}} \quad (3.30)$$

where

y_j is the depth (ft) or cover of herbs, shrubs or litter at microplot *j*.

δ_{jd} domain indicator variable which is 1 if microplot *j* is in the domain of interest *d* and 0 otherwise.

3.4.5 Slash Piles

Pile volume (ft^3/acre) or weight (tons/acre) in domain of interest *d,* is:

$$y_d = \frac{\sum_{j=1}^{4} \sum_{t} y_{jt} \delta_{jtd}}{\sum_{j=1}^{4} a_{jd'}} \qquad (3.31)$$

where

y_{jt} is the volume (ft^3) or weight (tons) of pile *t* at subplot *j*.

δ_{jtd} domain indicator variable which is 1 if pile *t* in subplot *j* belongs to the domain of interest *d* and 0 otherwise.

$a_{jd'}$ area of subplot *j* in the condition class of interest *d'*.

3.5 Change Estimation

Through the process of remeasuring the same CWD transects there is a moderate likelihood that the same CWD pieces will be remeasured in forest ecosystems with minimal disturbance and slow decay rates, albeit not the case for rapidly decaying FWD pieces. Despite this occurrence, few crews permanently mark CWD or FWD pieces. Therefore, unlike phase 2 standing-tree protocols that track individual trees over time, it is assumed that individual woody pieces will not be relocated and measured during remeasurement activities. Thus, it will not be possible to estimate components of change, but it will be possible to estimate net changes over large areas by comparing estimates of DWM components at two points in time or by combining information from different panels. Estimating change is currently an area of active research by FIA.

4.0 DWM ANALYTICAL GUIDELINES

To facilitate efficient and effective analysis of DWM data, forest-inventory analysts should be well versed in the sampling protocol, estimators, and management of DWM field data. Analysis of DWM data follows a hierarchy based on level of sophistication and required effort: field data, plot/condition level analyses, core tables, graphical summaries of population estimates, and maps. Analysis of DWM data also depends on access to actual data, with FIA analysts having access to actual plot locations. Users of external FIA data may have reduced access to plot locations and less ability to link DWM data to all phases of FIA's inventory program. However, most of the analysis in this section should be available to all.

4.1 Field Data

Although field data provide the base of any analytical exploration of DWM, analysts will only infrequently deal with raw data. Field data are organized into one of six tables (1.2-1.7). Researchers engaged in specific DWM studies can use these datasets where their investigations require unique processing and/or summarization of field data. An example of such an analysis is the relationship between CWD large-end diameters and total length on forest land in Maine (Fig. 4.1). In such instances, individual pieces or plots can be assumed to be a simple random sample in forest land to assess ecological dynamics, not a population estimate following procedures detailed in section 3. Alternatively, more complex models that incorporate the clustered structure of the data can be used. Otherwise, analysts may want to focus their resources on provided plot/condition and population estimates.

Although section 3.0 deals primarily with estimation of total variability including both sampling variability and measurement error, analysts should be aware of measurement errors and their potential impact on interpretation/application of field data. An initial examination of DWM measurement errors (Westfall and Woodall, in press) indicates poor repeatability of most DWM variables with some instances of bias, particularly for FWD. Given the highly disturbed and transitory nature of DWM, these repeatability results may be expected. However, it was further found that despite possible measurement errors, overall

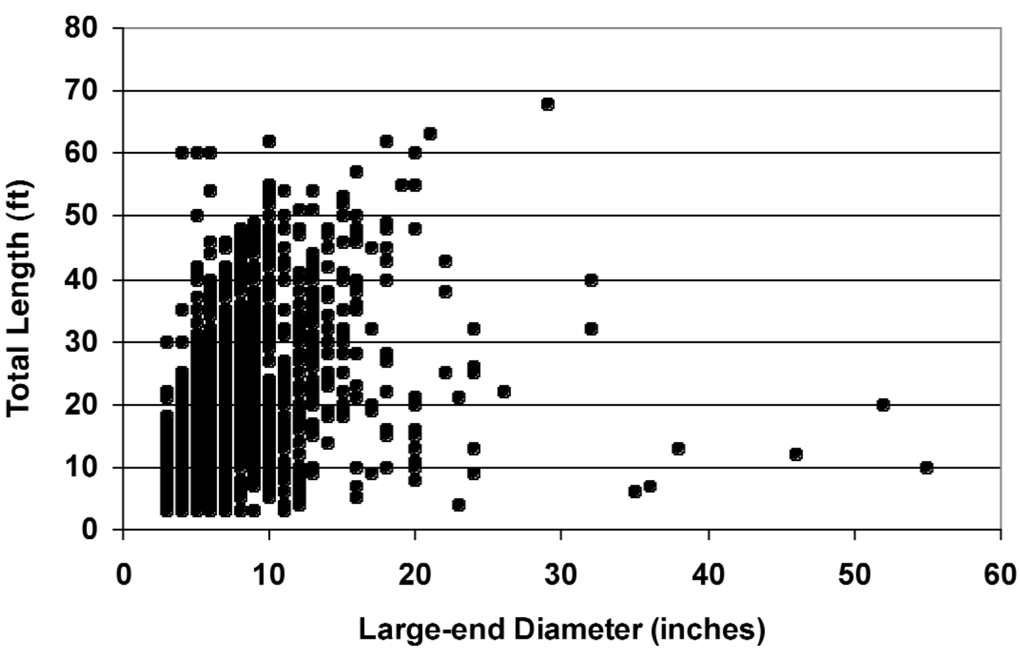


Figure 4.1. – Relationship between coarse woody debris large-end diameter and total length in Maine, 2001-2005.

plot-level estimates of DWM resources were not substantially affected.

4.2 Analyses at Plot/Condition Level

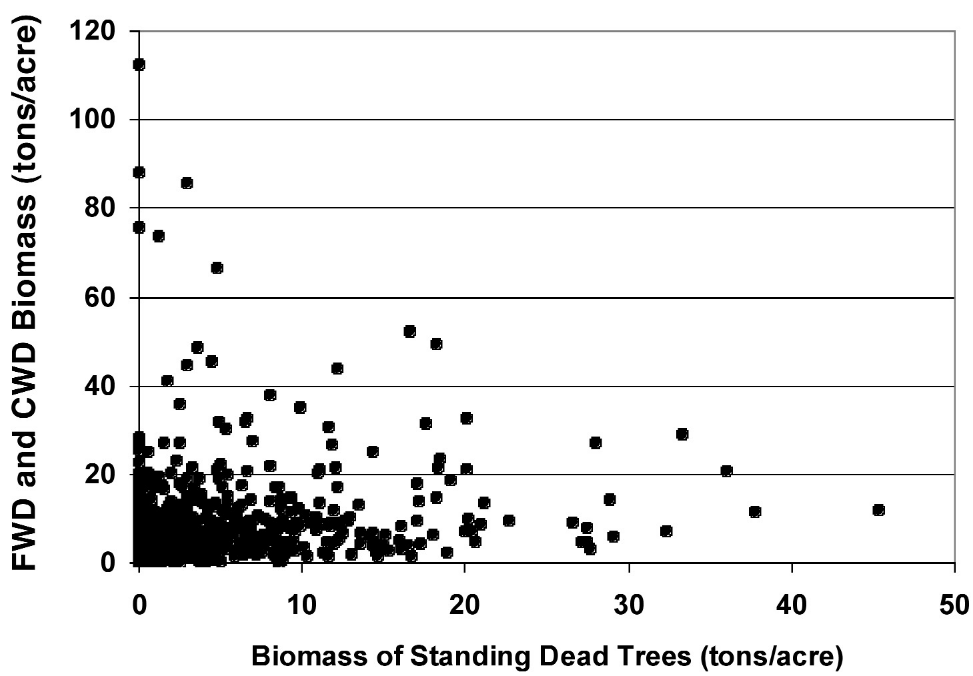
Most analysts will have access to estimates of DWM components at the plot and/or condition-class level. These outputs are not considered population estimates of a defined domain (e.g., red oak forests in Missouri). Instead, these estimates typically are expressed in per-unit-area values for individual plots or conditions (e.g., CWD cubic-foot volume/acre for plot x, condition class x) and are critical to modeling and mapping efforts (see section 3.4 and Appendix 7.2.3). For example, quantifying the relationship between standing dead trees (snags) and downed dead trees is critical to refining understanding of the ecological process of tree mortality contributions to the carbon cycle (Fig. 4.2). Another example is comparing the standing live-tree forest-type to the species composition of CWD pieces to evaluate forest change over long periods (Woodall and Nagel 2006). A final example is the mapping of individual plot-level estimates of CWD carbon stocks across the United States (Fig. 4.3). Such an analysis allows examination of spatial trends in carbon stocks across large scales.

4.3 Core Tables

Core tables provide population estimates of DWM attributes of interest for specified domains. The domains of core tables typically are forest-type groups in individual states. Core tables can be created using estimation procedures for population totals (e.g, total CWD tons in a region, see section 3.2 and Appendix 7.2.1) or ratio-estimation procedures (e.g., CWD tons per forest land acre in a region, see section 3.3 and Appendix 7.2.2). A series of core tables has been suggested for the DWM indicator based on the estimation procedures defined in this document (Tables 1.8, 4.1, 4.2, and 4.3). As estimation procedures are implemented in database procedures and provided to users, these core tables may be revised. These tables can serve as the basis of DWM investigations for most inventory analysts wishing to present user-friendly output to the public.

A fire science-oriented core table (Table 1.8) contains ratio estimates of fuel loadings (tons/acre) by forest-type group in a particular state. Holistic assessments of fire hazard can be made by combining the fire core table with other datasets such as phase 2 stand information and ancillary data (e.g., standing dead tree biomass, meteorological data, fuel-ladder estimates, and wildland-urban interface information).

Figure 4.2. – Relationship between standing dead trees biomass (tons/acre) and downed woody biomass (CWD+FWD) (tons/acre) on FIA inventory plots in the North-central United States, 2001-2005.



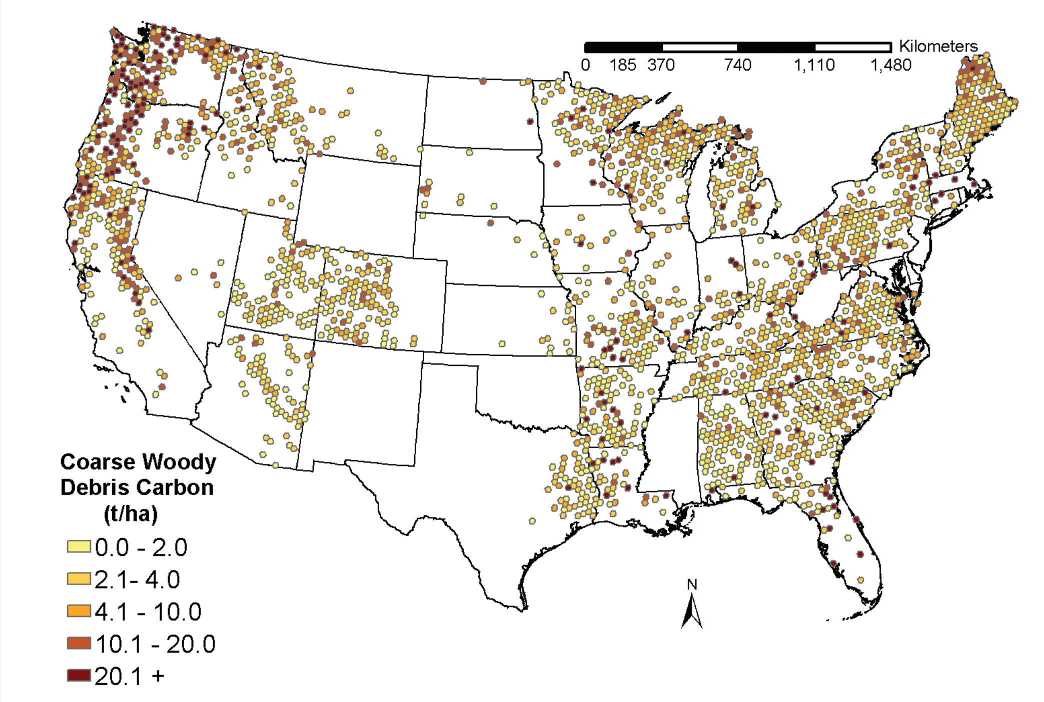


Figure 4.3. – Individual plot-level estimates of coarse woody debris carbon stocks (tonnes/ha) across the United States, 2001-2004 (plot values matched to EMAP hexagons).

Carbon-oriented core tables contain estimates desired by the carbon and greenhouse gas-accounting scientific community (Table 4.1). The core table contains population estimates of DWM component total carbon stocks on forest land in individual states. Because the soils indicator collects information on duff, litter, and small FWD, all DWM carbon components are delineated to avoid overlap of carbon pools (e.g., separation of FWD size classes). These delineations also match widely accepted carbon conventions: duff, forest floor, FWD, and CWD (Intergov. Panel on Clim. Change 1997). Analysts can use the carbon core tables in combination with other phases of the FIA inventory (e.g., phase 2 tree inventory, phase 3 soils, and phase 3 vegetative diversity indicator) to assess and monitor carbon pools of forest ecosystems for specified domains.

CWD core tables provide information about the quantity and quality of habitat for fauna with CWD niches (Table 4.2). CWD estimates also aid in assessing structural diversity in forest ecosystems. Therefore, the CWD core table contains ratio estimates of CWD attributes per unit of forest land by forest-type group in a particular state. The CWD attributes include large-end diameter distribution, decay-class distribution, CWD volume, and CWD cover. The distributions of CWD size and decay classes are represented by the estimated mean number of CWD pieces per acre.

The most appropriate core table for fuel loading information (shrubs and herbs) contains mean height and cover of shrubs and herbs by forest-type group for an individual state (Table 4.3). The mean cover of litter and fuelbed depth also is included in this core table which provides analysts with estimates that describe the fuel ladders for a given domain. It can be assumed that with all other environmental factors held constant the greater cover and heights of these fuel ladders indicate increased fire hazard.

4.4 Graphical Summaries

The estimates from DWM core tables and/or population estimation procedures can be displayed in numerous ways (Figs. 4.1, 4.2). The number of DWM plots in a defined domain determines which DWM summaries are possible. Analysis may not be possible if an analyst wishes to examine fuel loadings in an infrequent forest type in a state with a relatively small amount of

Table 4.1. – Carbon stocks by forest-type group and down woody component on forest land (million tons), State X, Year 1 to Year 2

Forest-type group	Forest floor		Fine woody debris			Coarse woody debris	Slash
	Duff	Litter	Small	Medium	Large		
Maple/beech/birch	12.22	3.55	12.22	3.55	12.22	3.55	0.00
Oak/hickory	8.84	3.67	8.84	3.67	8.84	3.67	2.22
Oak/pine	13.54	2.64	13.54	2.64	13.54	2.64	6.00
Elm/ash/cottonwood	18.21	5.24	18.21	5.24	18.21	5.24	0.00
Loblolly/shortleaf pine	9.87	2.33	9.87	2.33	9.87	2.33	5.55
White/red/jack pine	11.46	1.34	11.46	1.34	11.46	1.34	3.55
Other types	7.78	2.43	7.78	2.43	7.78	2.43	0
All forest-type groups	81.92	21.20	81.92	21.20	81.92	21.20	2.22

Table 4.2. – Mean attributes of coarse woody debris by forest-type group and attribute on forest land, State X, Year 1 to Year 2

Forest-type group	Large-end diameter distribution (inches)				Decay-class distribution					CWD volume	CWD cover
	3.0 – 7.9	8.0 – 12.9	13.0 – 17.9	18.0 +	1	2	3	4	5		
Maple/beech/birch	100.0	55.0	22.0	1.1	3.0	34.0	66.0	88.0	67.0	3.55	7.1
Oak/hickory	120.0	44.0	21.0	2.3	5.0	55.0	75.0	90.0	54.0	3.67	6.5
Oak/pine	233.0	35.0	23.0	4.0	7.0	45.0	67.0	98.0	56.0	2.64	8.9
Elm/ash/cottonwood	432.0	65.0	13.0	5.0	4.0	72.0	45.0	70.0	75.0	5.24	3.1
Loblolly/shortleaf pine	233.0	45.0	16.0	3.0	8.0	46.0	64.0	110.0	75.0	2.33	2.9
White/red/jack pine	244.0	76.0	31.0	7.0	9.0	75.0	79.0	87.0	58.0	1.34	6.6
Other types	234.0	75.0	24.0	2.1	2.2	44.0	97.0	96.0	77.0	2.43	5.4
All forest-type groups	265.0	45.0	12.0	1.3	7.8	65.0	76.0	86.0	78.0	1.34	4.9

Note: diameter and decay distribution units are CWD pieces/acre, CWD volume is cubic feet/acre, CWD cover is percent of acre covered by CWD

Table 4.3. – Mean attributes of shrub, herb, litter, and fuelbed by forest-type group on forest land, State X, Year 1 to Year 2

Forest-type group	Mean cover (percent)					Mean height (feet)				Fuelbed depth (feet)
	Live shrub	Dead shrub	Live herb	Dead herb	Litter	Live shrub	Dead shrub	Live herb	Dead herb	
Maple/beech/birch	60.5	5.5	77.6	3.3	96.0	3.1	0.9	0.4	0.1	2.2
Oak/hickory	44.3	7.2	59.0	5.4	89.7	2.3	0.7	0.3	0.2	1.8
Oak/pine	77.9	11.1	93.1	7.8	94.3	1.9	0.4	0.9	0.1	4.5
Elm/ash/cottonwood	69.4	3.6	88.4	2.2	95.1	2.2	0.2	0.6	0.2	2.1
Loblolly/shortleaf pine	78.4	5.9	83.1	2.7	89.6	1.1	0.8	0.1	0.3	3.7
White/red/jack pine	91.0	7.5	79.9	7.3	92.0	1.7	1.1	0.2	0.3	1.1
Other types	66.7	13.2	85.3	8.8	93.1	1.6	0.9	0.3	0.1	1.2
All forest type groups	75.6	8.8	81.7	5.4	91.0	1.9	0.8	0.4	0.2	1.6

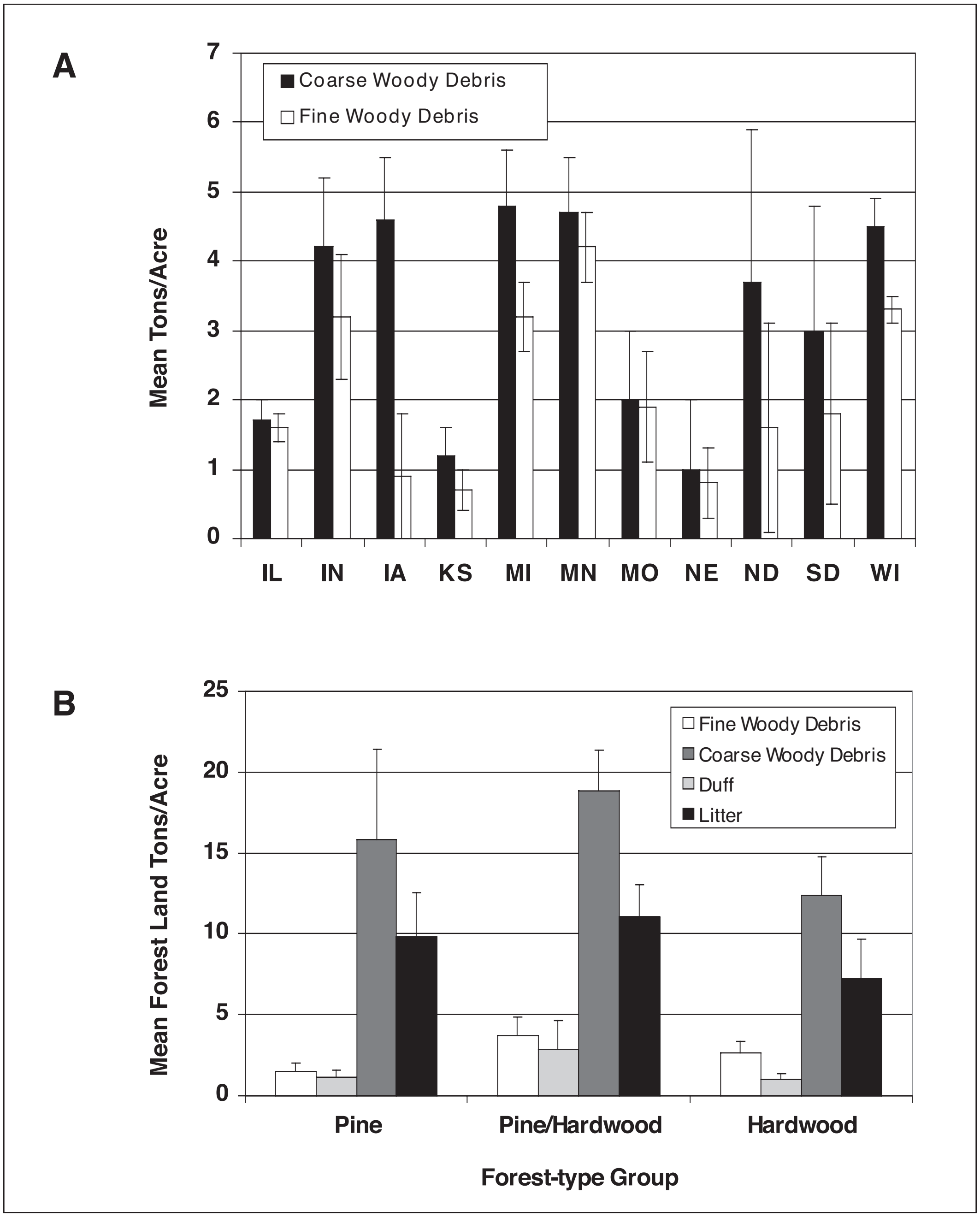
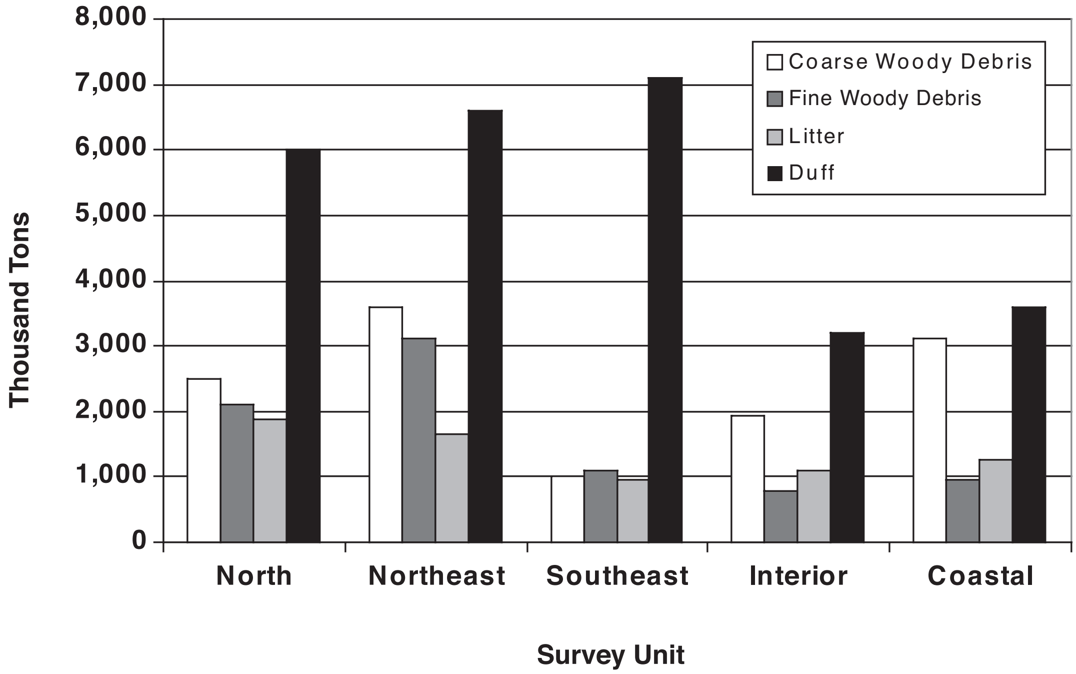


Figure 4.4. – Possible DWM summaries using population ratio estimates (with associated sampling errors) by two domains (A) states in a region and (B) forest-type groups in an individual state.

forest land (e.g., hemlock types in Maryland). In this case, the domain needs to be more inclusive of DWM plots due to the sparse sample intensity of phase 3 plots (e.g., hemlock types in New England states). Analysts also must determine the sampling errors associated with DWM estimates to determine which scale is appropriate for summary. A logical scale for summary of DWM data collected at the national base sampling intensity often is at the state or super-county level (Fig. 4.4a). DWM data summaries at scales smaller than a state might be permissible in states with extensive forest areas or when sample intensification occurs. Ratio estimates of population means (tons/acre) also can be displayed by broad forest-type groups within a state (Fig. 4.4b). Beyond ratio estimates, population totals can be displayed for a defined domain (Fig. 4.5). Defined areas again will depend on the sample size. If variances allow, analysts can produce a summary chart at super-county scales.

Figure 4.5. – Population total estimates of DWM components for an entire state by inventory survey-unit domain.



4.5 Maps

Maps of DWM components can be created several methods requiring various data inputs and levels of sophistication. At the very least, perturbed spatial locations of phase 3 inventory plots and associated estimates of DWM components are necessary to create maps. Ancillary datasets that aid the DWM map creation include but are not limited to ecological provinces, phase 2 data (e.g., live-tree volumes), and remotely sensed imagery (e.g., forest/nonforest maps). Estimates at the plot/condition (see section 3.4) are the primary data source for map creation.

The most basic type of map is one of perturbed plot locations with associated estimates of DWM components (Fig. 4.6). An analyst can use GIS software to display plot locations that are colored according to the associated DWM component. Although limited in creative scope, this basic map can be tailored to specific user requests, such as answering the rhetorical question, "What is the spatial distribution of FWD biomass in my area of interest based on FIA plots?"

A second type of DWM map can be created by linking ancillary datasets that are spatial in nature with the DWM inventory (Fig. 4.7). Typically, a population-ratio estimate (e.g., mean CWD volume per acre of forest land) can be mapped to defined domains (e.g., ecological province, Fig. 4.7). Mean values of DWM components can be estimated for any spatial data layer using procedures for estimating total population (section 3.3) and mapping results to domains defined in GIS layers (e.g., ecological provinces).

Estimates at the plot/condition level estimates can used to create "wall to wall" estimates of DWM attributes using interpolation techniques (Fig. 4.8). Interpolation entails predicting the values of DWM components between all sample points to create a continuous map of predicted DWM values (Woodall et al. 2004). DWM maps can be created in one of two ways by using interpolation methodologies. An analyst can constrain interpolation to forested areas as defined by FIA phase 1 stratification imagery, or an analyst can overlay an interpolated map of DWM values on that of a forest/nonforest map, thus masking out all nonforest areas (Fig. 4.8).

Maps can be created by intensive modeling based on FIA phase 2 data (Fig. 4.9). This process uses

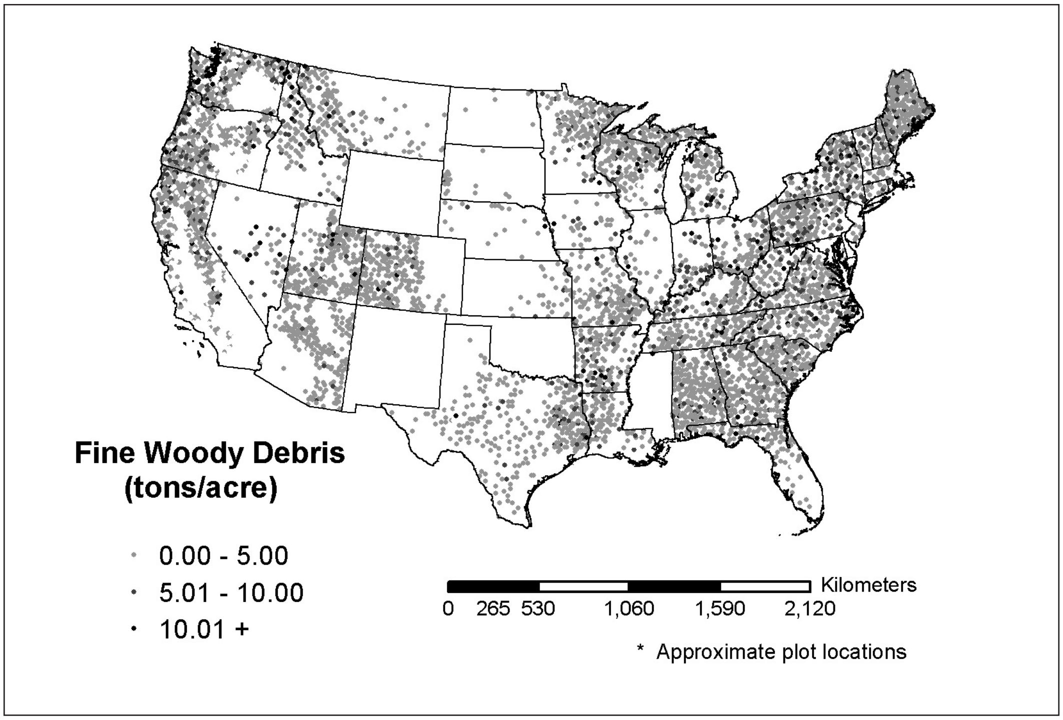


Figure 4.6. – Plot-level estimates of fine woody debris (tons/acre) in U.S. forest land, 2001-2005.

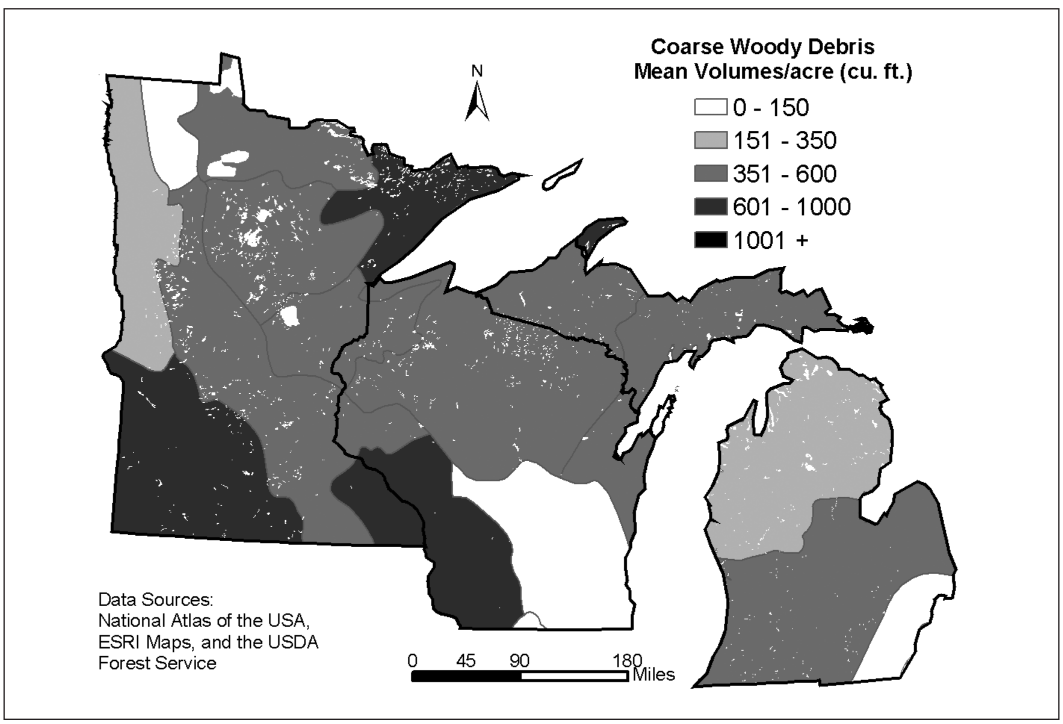
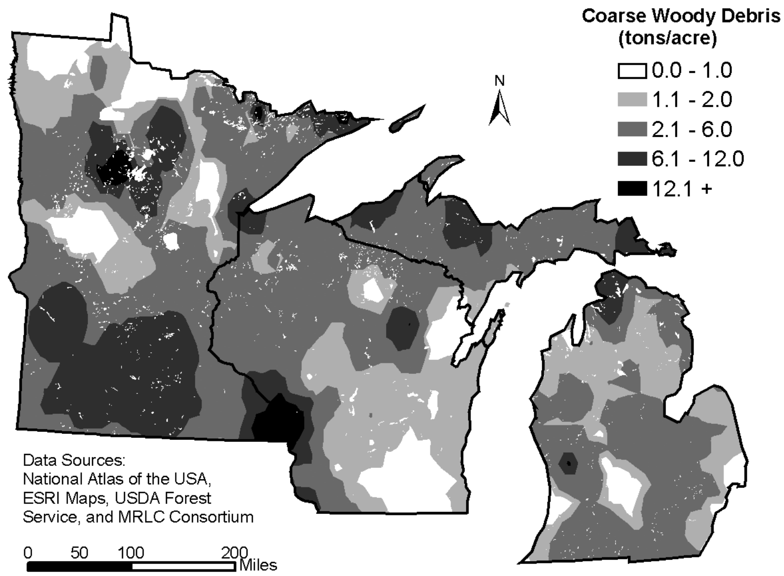


Figure 4.7. – Mean estimates of coarse woody debris volumes for North Central ecological province sections (Bailey 1995), 2001-2002.

Figure 4.8. – Example of inverse distance weighting interpolation technique for creating regional maps of DWM estimates.



Inverse distance weighting of coarse woody debris plot-level estimates, FIA phase 3 DWM plots, 2001-2003

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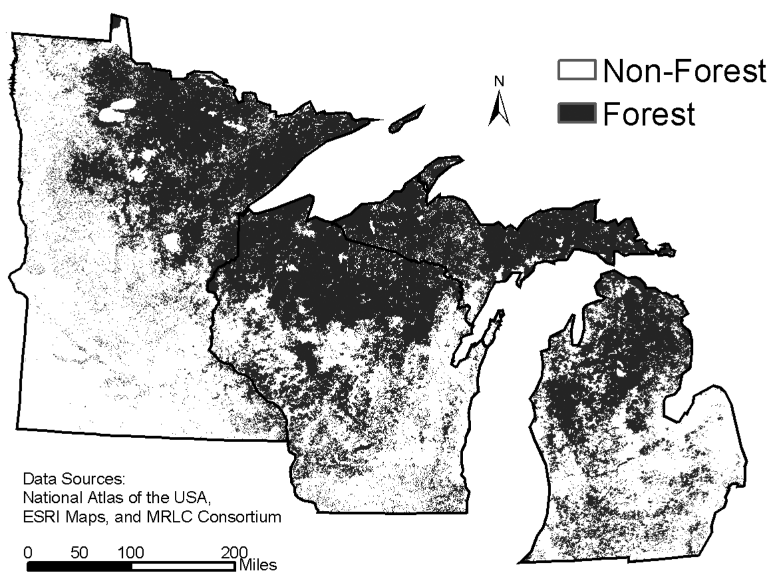

Forest/nonforest NLCD coverage for North Central states

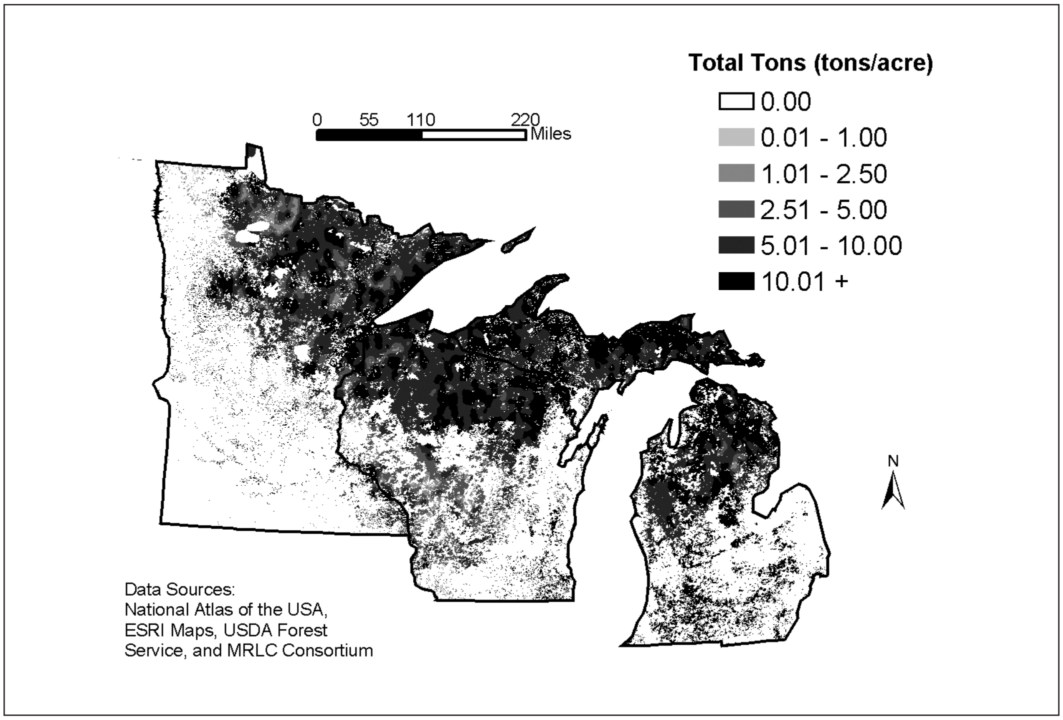

Figure 4.9. – Interpolation of predicted down fuels for Michigan, Minnesota, and Wisconsin FIA phase 2 plot attributes based on phase 2/phase 3 fuel model (McRoberts et al. 2004).

both phase 2 and 3 data to create models such that DWM components are estimated for every phase 2 plot. Once satisfactory models are created, DWM components can be estimated for every phase 2 plot and mapped (Fig. 4.9). Although the sampling intensity is much greater for phase 2 plots, the efficacy of this methodology depends on the explanatory power of the models established between phase 2 and 3 plots.

Finally, although DWM attributes (e.g., CWD biomass) may be both correlated and directly modeled with phase 2 attributes (e.g., standing live tree basal area), there are numerous non-parametric methods that serve as an interesting alternative. Non-parametric methods may predict DWM attributes as a weighted average of the values of neighboring observations. In this process, neighbors are chosen from a database of previously measured observations (known pairs of phase 2 and phase 3 attributes). Often these non-parametric methods are referred to as imputation techniques where values are assigned to observations that lack such data. Given the relatively sparse sample intensity of DWM plots relative to the diversity of forest ecosystem components they estimate, non-parametric methods may offer several advantages compared to using parametric regression models to predict mean values.

The mapping of DWM indicator data is a relatively recent analytical undertaking that allows maximum freedom for analysts. Every method for producing maps of DWM estimates has advantages and disadvantages, and it is suggested that analysts explore all options and be aware of recent scientific developments.

4.6 Science Areas

There are numerous knowledge gaps in the study of DWM ecology in forest ecosystems that may help direct DWM research and inventory reporting. Knowledge gaps can be broadly summarized by discipline: wildlife, fire/fuels, carbon, snags, structure, and nutrient cycles. With regard to wildlife sciences, there are numerous knowledge gaps in the effect of CWD decay and size distributions on habitat, particularly for specific wildlife species. Particularly with respect to the DWM indicator, there has been a lack of analysis of hollow codes inventoried by the FIA program. With respect to the fire and fuel sciences, there is both a great public need and a significant knowledge gap in the following areas:

mapping of fuel loadings, population summaries by state/region, linkage between the FIA inventory and models of fire behavior, comprehensive assessments of fire danger by FIA plot, and linkages between phase 2 and DWM plots. With regard to assessments of carbon stocks, there are numerous knowledge gaps both in the estimation procedures and basic analyses. Carbon content and bulk density of DWM components are not measured, but calculated using volume-to-biomass-to-carbon conversion constants. Increasing our understanding of how bulk density and carbon content vary by species, tree size, and decay class would, in turn, refine DWM carbon-population estimates. We also need to understand how DWM carbon stocks such as CWD vary by stand structure, management activities, and change over time. With respect to standing dead trees, there has been a lack of analysis of both snag and CWD (as defined by FIA) attributes collectively. Because snags often are precursors of CWD recruitment, increasing our understanding of the relationship between DWM and snags could be beneficial in predicting DWM attributes based on the phase 2 inventory. With regard to assessments of stand structure, DWM is a critical component of the overall structure of stands but often is omitted in most assessments of structure. Including DWM attributes in assessments of stand structure probably would require new structure indices. Finally, there has been a lack of analysis of DWM inventory data with respect to nutrient cycling. The DWM inventory can be used to increase our understanding of nutrient cycles in forest ecosystems at the landscape scale.

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6.0 GLOSSARY

Coarse Woody Debris (CWD): Pieces or portion of pieces of down dead wood with a minimum small-end diameter of at least 3 inches and a length of at least 3 feet (excluding decay class 5). CWD pieces must be detached from a bole and/or not be self-supported by a root system with a lean angle more than 45 degrees from vertical.

Decay Class: Rating of individual coarse woody debris according to a 5-class decay scale defined by the texture, structural integrity, and appearance of pieces. Scale ranges from freshly fallen trees (class 1) to totally decomposed cubicle rot heaps (class 5).

Down Woody Materials (DWM): Collective attributes estimated by the DWM indicator. Consists primarily of the following down and dead forest materials: fine woody debris, coarse woody debris, duff, litter, slash, live and dead herb and shrubs, and fuelbed depths.

Duff: Organic forest-floor layer consisting of decomposing leaves and other organic material in which individual plant parts are not recognizable.

Fine Woody Debris (FWD): Pieces or portion of pieces of down woody debris with a diameter less than 3 inches at the point of transect intersection; excludes dead branches attached to standing trees, dead foliage, bark fragments, and cubicle rot.

Fuelbed: Accumulated mass of all DWM components above the top of the duff layer (excluding live shrubs/herbs).

Herbs: Nonwoody vascular plants including but not limited to ferns, mosses, lichens, sedges, and grasses.

Line-Intersect Sampling (LIS): Sampling technique by which sampling planes are installed in defined areas of interest whereby the intersection of down woody debris with sampling planes is used to estimate attributes of coarse and fine woody populations.

Litter: Forest-floor layer of freshly fallen leaves, needles, twigs, cones bark chunks, dead moss, dead lichens, dead herbaceous stems, and flower parts.

Pile Density: Density of coarse woody debris in slash piles within the volume defined by the shape code and dimensions estimated by field crews; also known as packing ratio.

Shrubs: Vascular plants with woody stems exclusive of plants defined as trees by FIA.

Slash: Otherwise known as residue piles, coarse woody debris in piles created directly from human activity or from natural events that prohibit safe measurement by transects.

Time-Lag Fuel Classes: Fuel classes defined by the amount of time it takes for moisture conditions to fluctuate. Larger coarse woody debris takes longer to dry out than smaller fine woody pieces (small FWD=1 hour, medium FWD=10 hours, large FWD=100 hours, CWD=1,000+ hours).

Transect Diameter: Diameter of coarse woody pieces at the point of intersection with sampling planes.

Transect Segment: Sections of transects that lie entirely within one condition class whereby one 24-foot transect that lies across two condition classes will have two transect segments.

Y Transect: Spatial arrangement of sampling transects on FIA subplots whereby they radiate out from the subplot center at obtuse angles of 120 degrees from each other.

7.0 APPENDICES

7.1. Line-intersect Sampling of Coarse and Fine Woody Debris

Line-intersect sampling (LIS) differs from the fixed-area plots used in phase 2 of the FIA inventory. It may be a novel concept for some analysts, so we present background on its development and application. The fundamental concept of LIS, also known as line-intercept and planar-intercept sampling, is that sampling of down woody debris occurs along transect lines. Before LIS was introduced, down woody debris was sampled by tallying down woody pieces within a defined area. Warren and Olsen (1964) introduced the first application of the LIS technique for estimating logging residue in New Zealand. On the basis of this work, there have been a number of refinements and alterations of LIS that are reflected in the FIA methods. Van Wagner (1968) introduced a method for requiring only field measurements of the diameter of each piece at transect intersection for determining volume, discussed potential sources of bias when using LIS, and suggested the use of L- or Y-shape transects. de Vries (1973) and de Vries and van Eijnsbergen (1973) expanded LIS theory, including populations of linear particles of arbitrary shape, and proposed various LIS estimators, many of which are used by FIA. One of the most widely used manuals based on this work is Brown's (1974) handbook on inventorying DWM. It remains a key reference for determining fuel loadings across the Western United States. Hazard and Pickford (1986) and Bell et al. (1996) examined transect shape and the effect of the orientation of the pieces of wood in estimation, and concluded that a Y-shape transect is the most efficient transect design. Kaiser (1983) generalized LIS for particles of any shape and provided a comprehensive treatment from a design-based perspective. The most detailed treatment of LIS theory for CWD estimation is in de Vries (1986, chapter 13). Recent reviews include Marshall et al. (2000) and Waddell (2002), the latter from an FIA perspective.

7.1.1. Background and Notation

Here we derive the LIS estimator specifically for estimating coarse and fine woody debris. For the purpose of sampling woody debris, each log is reduced to its centerline axis. Therefore, we consider a population of discrete lines of arbitrary shape, possibly branched, distributed over a region A of area equal to *A*. We do not make assumptions about the characteristics of the lines or their location or orientation. However, we ignore edge effects so that the estimators apply only to pieces in the interior of A. The definition of the region of interest and the treatment of edges by FIA is described in Scott et al. (2005).

Let y_t be any fixed, measurable attribute of the *t*-th piece (e.g., volume). We are interested primarily in estimating the total amount of the attribute of interest in the region A, defined as the sum of y_t over all the pieces in the population,

$\tau = \sum_{t=1}^{N} y_t$, where *N* is the number of pieces in A. Other parameters, such as values per unit area, follow directly by dividing the total τ by the area *A*, or by using ratio estimators (section 3.3).

The population is sampled with a straight-line transect of length *L*. A piece is included in the sample if its centerline is intersected by the transect, and the number of intersections is recorded. Then, an unbiased estimator of the total τ is:

$$\hat{\tau} = \sum_{t=1}^{n} \frac{y_t z_t}{E(z_t)} \qquad (7.1)$$

where the sum is over the pieces intersected by the transect, n is the number of intersected pieces, z_t is a random variable that counts the number of intersections between the transect and the piece, and $E(\bullet)$ is the expectation, or mean, operator.

To prove that the estimator 7.1 in unbiased, we need to show that its expected value is the parameter of interest, that is, $E(\hat{\tau}) = \tau$. First note that if a piece is **not** intersected by the transect, the number of intersections $z_t = 0$. Therefore, the sum in equation 7.1 can be extended from the pieces included in the sample, n, to all the pieces in the population, N:

$$\hat{\tau} = \sum_{t=1}^{n} \frac{y_t z_t}{E(z_t)} = \sum_{t=1}^{N} \frac{y_t z_t}{E(z_t)} \tag{7.2}$$

The only random variable in equation 7.2 is z_t , and the expectation is a linear operator, so unbiasedness follows:

$$E(\hat{\tau}) = E\left(\sum_{t=1}^{N} \frac{y_t z_t}{E(z_t)} \right) = \sum_{t=1}^{N} \frac{y_t E(z_t)}{E(z_t)} = \sum_{t=1}^{N} y_t = \tau$$

Therefore, to obtain an unbiased estimator of the total τ, all that is needed is the ability to calculate the expected number of intersections, $E(z_t)$, for those pieces intersected by the transect.

7.1.2. Expected Number of Intersections Between Transect and Piece of Wood

The derivation of the expected number of intersections between the transect and a piece of wood of arbitrary shape follows three steps. First, it is derived for a hypothetical population of straight-line pieces. Then, as an intermediate step, it is extended to a population of pieces formed by connected, straight-line segments. Finally, it is generalized to a more realistic population of continuous lines of arbitrary shape, such as log centerlines. A different derivation is found in de Vries (1986, chapter 13) and Kaiser (1983, example 2d).

The population is sampled uniformly at random with a straight-line transect of length L, specifically: (1) the transect midpoint might lay anywhere in A with equal probability, so that the probability that the midpoint falls in any subset, B, is the area of B divided by the area of A; (2) the transect azimuth, θ, can take any value between 0 and 180 degrees (π radians) with equal probability, so that the probability distribution of θ is uniform in the interval $[0, \pi]$; (3) the location and azimuth of the transect are determined independently.

Population of straight lines

Consider a population of discrete, straight-line pieces. Figure 7.1(a) shows an example of a portion of the region of interest A, highlighting an arbitrary piece. Figure 7.1(b) shows a possible location of the transect, in which the t-th piece is intersected. Because both the transect and the piece are straight lines, there can be only one intersection at most. Therefore, z_t is an indicator variable, that is, 1 if the piece is intersected, or 0 otherwise. By definition, the expected value of the random variable z_t is the probability of intersection, $E(z_t) = P(z_t = 1)$.

To derive the probability that the transect intersects the t-th piece, we first fix the transect azimuth to an arbitrary angle θ. The transect intersects the piece if and only if its center falls in the area shaded in

Figure 7.1(c). This area is $Ll_t \sin(\theta_t)$, where l_t is the length of the piece and θ_t is the angle between the piece and the transect. Therefore, conditional on the value θ, and because of condition (1), the probability that the transect intersects the piece is the area $Ll_t \sin(\theta_t)$ divided by the area of A:

$$P(z_t = 1 \mid \theta) = \frac{Ll_t \sin(\theta_t)}{A} \tag{7.3}$$

The azimuth of the piece is fixed and constant. θ_t, the angle between the piece and the transect, is calculated as the azimuth of the piece, a constant, minus θ. Thus, the distribution of θ_t also is uniform on the interval $[0, \pi]$ (condition (2)), with probability density $f(\theta) = 1/\pi$. We can apply the law of total probability to obtain the probability of intersection, unconditional of transect orientation, as the conditional probability [7.3], averaged over all possible values of θ:

$$E(z_t) = P(z_t = 1) = \int_0^\pi P(z_t = 1 \mid \theta) f(\theta) d\theta = \int_0^\pi \left[\frac{Ll_t \sin(\theta)}{A}\right] \frac{1}{\pi} d\theta = \frac{2Ll_t}{\pi A} \tag{7.4}$$

Population of segmented lines

Consider a population of lines composed of an arbitrary number S_t of connected, straight-line segments, each of length l_{ts}. We do not make assumptions about how the segments are arranged or whether the piece is branched or a single line. Define a random variable, z_{ts}, that takes the value of 1 if the s-th segment of the t-th piece is intersected by the transect and 0 otherwise. Let

$z_t^{(S)} = \sum_{s=1}^{S_t} z_{ts}$ be a random variable that counts the number of intersections between the t-th piece and the transect, and

$l_t = \sum_{s=1}^{S_t} l_{ts}$ the total length of the piece. Then, from equation 7.4 and the linear properties of the expectation operator,

$$E\left(z_t^{(S)}\right) = E\left(\sum_{s=1}^{S_t} z_{ts}\right) = \sum_{s=1}^{S_t} E(z_{ts}) = \sum_{s=1}^{S_t} \frac{2Ll_{ts}}{\pi A} = \frac{2L}{\pi A} \sum_{s=1}^{S_t} l_{ts} = \frac{2Ll_t}{\pi A} \tag{7.5}$$

Population of lines of arbitrary shape

The generalization to continuous linear pieces of finite length and arbitrary shape follows by taking the limit of a segmented piece as $S_t \to \infty$. The t-th piece is divided into S+1 points, which define S segments of length $l_{ts} = l_t/S$. In the limit, this segmented line approaches the arbitrarily shaped line. Then, substituting equation 7.5, the expected number of intersection is:

$$E(z_t) = E\left(z_t^{(\infty)}\right) = \lim_{S\to\infty} E\left(z_t^{(S)}\right) = \lim_{S\to\infty} \sum_{s=1}^{S} \frac{2Ll_{ts}}{\pi A} = \lim_{S\to\infty} \sum_{s=1}^{S} \frac{2L(l_t/S)}{\pi A} = \frac{2Ll_t}{\pi A} \tag{7.6}$$

Therefore, the expected number of intersections between a piece and the transect is exactly the same whether the piece is straight line or a line of arbitrary shape. It depends only on the piece's length, not its shape (de Vries 1986: 272, Kendall and Moran 1963: 71).

7.1.3. Line-intersect Sampling Estimator: Straight-line Transect

From eqs. 7.1 and 7.6, the LIS estimator of the population total of a measurable attribute, τ, for linear pieces of arbitrary shape is:

$$\hat{\tau} = \sum_{t=1}^{n} \frac{y_t z_t}{E(z_t)} = \frac{\pi A}{2L} \sum_{t=1}^{n} \frac{y_t z_t}{l_t} \tag{7.7}$$

where the sum is over the pieces intersected by the transect (*n*). In this equation, z_t is the number of times that the *t*-th piece is intersected by the transect. To facilitate data recording in the field rather than tallying the number of intersections, FIA tallies each piece as many times as intersected by the transect. Then, the equation can be written as:

$$\hat{\tau} = \frac{\pi A}{2L} \sum_{t=1}^{n} \frac{y_t z_t}{l_t} = \frac{\pi A}{2L} \sum_{t=1}^{n} \sum_{u=1}^{z_t} \frac{y_t}{l_t} = \frac{\pi A}{2L} \sum_{t=1}^{n_z} \frac{y_t}{l_t} \tag{7.8}$$

where the last sum is over the number of intersections, $n_z = \sum_{t=1}^{n} z_t$, not the number of pieces.

If the attribute of interest is the total volume of down wood, then y_t is the volume of the *t*-th piece. This volume can be estimated by realizing that the diameter at the intersection is a random sample of the diameter of the piece (De Vries 1986: 258), so that

$y_t = \frac{\pi}{4} DI_t^2 l_t$ where *DI* is the diameter at the intersection, is an estimate of the volume of the piece.

Substituting in eq. 7.8,

$$\hat{v} = \frac{\pi A}{2L} \sum_{t=1}^{n_z} \frac{(\pi/4) DI_t^2 l_t}{l_t} = \frac{\pi^2 A}{8L} \sum_{t=1}^{n} DI_t^2 = \frac{\pi^2 A}{8L} n\overline{QMDI}^2 \tag{7.9}$$

where $\hat{v}$ is the estimated total volume and $\overline{QMDI}$ the quadratic mean diameter at the intersection. This is the equation used by FIA to estimate fine woody debris.

7.1.4. Line-intersect Sampling estimator: Segmented Transects

Extension to a Y-shape transect, or to a cluster of M lines arranged in any shape, is straightforward: the estimator is applied to each arm of the transect, and the estimates averaged (Van Wagner 1968). Let $\hat{\tau}_m$ be the estimator in eq. 7.7, unbiased for a straight-line transect, applied to the *m*-th arm of the transect. Then, the average over *M* arms, regardless of transect configuration, always is unbiased:

$$\hat{\tau} = \frac{1}{M} \sum_{m=1}^{M} \hat{\tau}_m = \frac{1}{M} \sum_{m=1}^{M} \left(\frac{\pi A}{2L} \sum_{t=1}^{n_m} \frac{y_t z_{mt}}{l_t} \right) = \frac{\pi A}{2ML} \sum_{m=1}^{M} \sum_{t=1}^{n_m} \frac{y_t z_{mt}}{l_t} = \frac{\pi A}{2ML} \sum_{t=1}^{n} \frac{y_t z_t}{l_t} \tag{7.10}$$

where the last sum is over the pieces intersected by any branch of the transect, *ML* is the total transect length, z_{nt} is the number of the number of intersections between the *t*-th piece and the *m*-th branch of the transect, and

$z_t = \sum_{m=1}^{M} z_{mt}$ is the total number of intersections between the *t*-th piece and any branch of the transect. Note that eqs. 7.7 and 7.10 have the same form. Therefore, the estimator is exactly the same whether a single-line or a cluster of lines is used.

7.1.5. Orientation Bias

The derivation discussed in section 7.1.2 for populations of straight-line pieces was proposed by Buffon in 1777 and generally is known as Buffon's "needle" problem. It concerns the probability that two straight lines intersect — one fixed at an arbitrary location and orientation within a region, and one randomly thrown into that region (needle). This is simply a probability exercise and does not specify whether the needle should be the transect or the piece of wood. If the transect is the needle then inference is based on the sampling design and the expectation in eq. 7.4 is valid for any location and orientation of the pieces. Alternatively, the transect may be set at a fixed position and orientation and the pieces of wood are assumed to be randomly distributed in A. If this distribution follows the conditions listed in section 7.1.2, i.e., that any piece location and orientation are equally likely, then eq. 7.4 gives the expected value of the number of intersections. It is important to note that those conditions are only sufficient, not necessary for eq. 7.4 to be valid. Most of the initial work on LIS for estimating down wood was developed under the assumption of a population of pieces distributed at random (e.g., Warren and Olsen 1964, Van Wagner 1968, de Vries 1973). Both Kaiser (1983) and de Vries (1986) discussed estimation in a fixed population of arbitrary pieces.

If the conditions under which an estimator is derived are not met, bias is possible. Orientation bias, which can occur if the actual orientation (of pieces or transect) is not uniformly at random, has received much attention. Van Wagner (1968) suggested the use of transects oriented in various directions to minimize this bias. Although he was working under the assumption of a randomly oriented population of pieces, the same conclusion applies when a random orientation of the transect is postulated but not fully met. For a Y-shape transect, maximum bias occurs if all the pieces are oriented in exactly the same direction and the angle between the pieces and any branch of the transect is 30 or 0 degrees. Then, upper and lower bounds for the bias are +5 and -9 percent, respectively. Obviously, in a real population not all pieces are oriented exactly in those directions so that, even if there is a dominant orientation, the actual bias likely will be negligible. The primary issue with respect to transect configuration is efficiency (both statistical and practical). Without knowledge of the actual distribution of the pieces of wood in the study population, any discussion of the relative statistical efficiency of straight-line versus Y-shape transects is speculation. Bell et al. (1996) and Hazard and Pickford (1986), using a series of simulation studies to examine transect configuration and concluded that, under their simulation assumptions, a Y-shape configuration is the most efficient in both variance and field implementation.

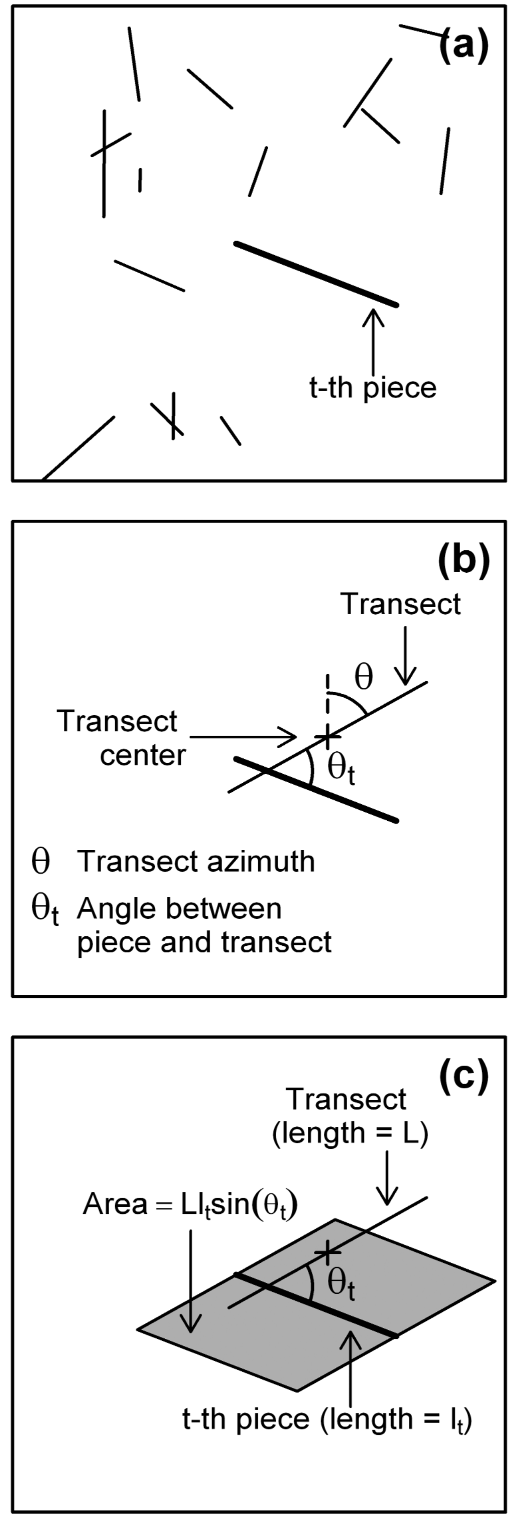


Figure 7.1. – Line-intersect sampling: the process used to calculate a piece's inclusion probability.

7.2. Examples

In this section the estimation procedures described in section 3.0 are illustrated with three examples. The first concerns estimating the total biomass of coarse woody debris in a population. The first of three steps is to compute the total biomass in each plot, corrected for plots partially outside of the population (section 3.1.1). In the second step, the computed plot values are averaged to the stratum level (section 3.2). Finally, the averages for each stratum are combined to arrive at an estimate of the total for the population (section 3.2). Because the total amount of biomass is the parameter of interest regardless of species or any other attribute, all pieces are included and the domain indicator variable is always 1 (domain restrictions are considered in the second example).

The second example illustrates a ratio estimator with domain restrictions. We estimate the mean number of large pieces of woody debris per acre of Douglas-fir forest. Estimating a ratio requires estimating the population total of both the numerator (number of large pieces) and denominator (acreage in Douglas-fir forest type), following the steps in the first example. The domain for the numerator is based on both an attribute of the piece (defined here as large end diameter greater than 20 inches) and the forest condition in which it is located (Douglas-fir forest type), while the domain of the denominator is singly defined by a forest condition (Douglas-fir type). The total acreage in Douglas-fir forest can be estimated from phase 2 mapped plots; however, we recommend and will use transect data as described in section 3.3.2.

The third example illustrates the estimation of a DWM attribute for a portion of a plot. We estimate the biomass of CWD in accessible forest land for one plot, following procedures described in section 3.4.

We illustrate the estimation procedures using a hypothetical stratum composed of four plots. Each plot represents a different situation that may be encountered when analyzing FIA DWM data. One plot could not be measured because the property owner denied access and a second plot was only partially measured because a portion was too hazardous to be sampled (e.g., cliff or meth lab). The other two plots straddle two condition classes: one was partially nonforested while the other straddled two forest types. Each of those situations is treated differently as is seen in the examples.

7.2.1. Estimating Population of Total Biomass in Coarse Woody Debris

Compute values at plot level

The first step is computing the adjustment factor for partial plots outside the population, $\overline{p}_h^{CWD}$, following eq. 3.2. Table 7.2.1 shows the plot and condition class data that are needed to compute this equation. The stratum contains four plots, but the owner denied access to one of them. Thus, the number of observed plots in the stratum (n_h) is three and the total length of transect that could potentially be observed is 864 ft (3 plots * 12 transects per plot * 24 ft per transect). The length of transect actually measured in the stratum is calculated using information provided in Tables 7.2.1 and 7.2.2. Field crews record the slope and slope distance of each transect segment, from which the horizontal length of each segment, L_{hijmk}, is calculated. The horizontal distance is provided by default in the standard FIA tables, but can be calculated as:

$$L_{hijmk} = \frac{L_{hijmk}^{S}}{\sqrt{1 + \left(\%\ \text{slope}_{hijk} / 100\right)^2}}$$

where L_{hijmk}^{S} and $\%\ \text{slope}_{hijk}$ are the length and slope of the transect, respectively.

Each segment also is assigned to a condition class. From Table 7.2.1, the only condition class outside of the population is that labeled 2 in plot 3. This portion of the plot was considered hazardous and could not be accessed. Note that condition class 2 in plot 1 is not forested. However, although nonforested land never is a domain of interest, nonforested conditions are part of the population and are observed. Therefore, the indicator variable, δ_{hijmk} takes the value of 1 for all segments except those in condition class 2 of plot 3. The length of transect measured,

$\sum_{i=1}^{n_h}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{k=1}^{K_{hijm}} L_{hijmk}\delta_{hijmk}$, can be calculated by simply summing column $L_{hijmk}\delta_{hijmk}$ in Table 7.2.2.

Based on these calculations, $\overline{p}_h^{CWD}$ is:

$$\overline{p}_h^{CWD} = \frac{\sum_{i=1}^{n_h}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{k=1}^{K_{hijm}} L_{hijmk}\delta_{hijmk}}{12Ln_h} = \frac{781.3}{864} = 0.9043$$

The next step entails computing eq. 3.1 for each observed plot in the stratum. Table 7.2.3 provides the information for each intersected piece of down wood. To compute the total biomass, we first calculate the piece's volume using equation 1 or 2 in Table 3.1, as appropriate. Next, the piece's biomass is calculated by multiplying the volume by the bulk density of the species' wood (Appendix 7.5), a decay-class mass-reduction factor (Table 3.2), and a constant to convert to proper units (eqs. 3 and 4, Table 3.1). Table 7.2.3 shows the computed volume and biomass of each piece in cubic feet and pounds, respectively. Plot biomass is computed from equation 3.1, where y_{hijmt} is the biomass of each piece and the unit conversion factor to tons per acre is 43560/2000. Because we are interested in total biomass, all pieces are in the domain of interest and δ_{hijmtd} always is 1. Example 2 illustrates the case when domain restrictions are imposed in the pieces of wood and, as a consequence, δ_{hijmtd} is not 1 for all the pieces. Eq. 3.1 can now be computed for each plot:

Plot 1: $$y_{h1} = \left(\frac{43560}{2000}\right)\left[\frac{(\pi/2)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}\frac{y_{hijmt}\delta_{hijmtd}}{l_{hijmt}}\right] =$$

$$= \left(\frac{43560}{2000}\right)\left(\frac{(\pi/2)}{12*24*0.9043}\right)\left(\frac{19.7}{9}+\frac{8889.6}{98}+\frac{1356.3}{70}+\frac{11029.6}{139}\right) = 25.17\ \text{tons/acre}$$

Plot 2: $$y_{h2} = 10.06\ \text{tons/acre}$$

Plot 3: $$y_{h3} = 34.85\ \text{tons/acre}$$

Computed stratum mean and variance

The next step combines the data from each plot to yield an average for the stratum (eq. 3.12):

$$\overline{Y}_{hd} = \frac{\sum_{i=1}^{n_h} y_{hid}}{n_h} = \frac{25.17+10.06+34.85}{3} = 23.36\ \text{tons/acre}$$

with estimated variance (eq. 3.13):

$$\text{var}\left(\overline{Y}_{hd}\right)=\frac{\sum_{i=1}^{n_h}\left(y_{hid}-\overline{Y}_{hd}\right)^2}{n_h\left(n_h-1\right)}=\frac{\left(25.17-23.36\right)^2+\left(10.06-23.36\right)^2+\left(34.85-23.36\right)^2}{3\left(3-1\right)}=52.03\ \left(\text{tons/acre}\right)^2$$

Total biomass and its variance

The estimated total biomass is obtained by combining information from all the strata in the population. Table 7.2.4 provides the stratum data from a hypothetical population, where stratum 1 is the stratum illustrated in this example. For stratified sampling, the estimated total biomass is calculated from eq. 3.14:

$$\hat{Y}_d = A_T\sum_{h=1}^{H}W_h\overline{Y}_{hd}=1602000\left(\frac{403200}{1602000}23.36+\frac{470400}{1602000}0.98+\frac{728400}{1602000}11.40\right)=18.18\text{ million tons}$$

with estimated variance (eq. 3.15)

$$\text{var}\left(\hat{Y}_d\right)=\frac{A_T^2}{n}\left[\sum_{h=1}^{H}W_hn_h\ \text{var}\left(\overline{Y}_{hd}\right)+\sum_{h=1}^{H}\left(1-W_h\right)\frac{n_h}{n}\text{var}\left(\overline{Y}_{hd}\right)\right]=$$

$$=\frac{\left(1602000\right)^2}{15}\left\{\begin{array}{l}\left[\frac{403200}{1602000}\times3\times52.03+\frac{470400}{1602000}\times5\times0.96+\frac{728400}{1602000}\times7\times2.87\right]+\\+\left[\left(1-\frac{403200}{1602000}\right)\times\frac{3}{15}\times52.03+\left(1-\frac{470400}{1602000}\right)\times\frac{5}{15}\times0.96+\left(1-\frac{728400}{1602000}\right)\times\frac{7}{15}\times2.87\right]\end{array}\right\}=$$

$$=10.02\ \left(\text{million tons}\right)^2$$

The standard error is estimated as the square root of the variance:

$$SE\left(\hat{Y}_d\right)=3.17\text{ million tons}$$

7.2.2 Number of Large Pieces of Woody Debris per Acre of Douglas-fir Forest

In this example we estimate the total number of pieces of CWD with a large-end diameter greater than 20 inches per acre of Douglas-fir forest type. The first task when estimating a ratio involves computing the population total for both the numerator and denominator, as described in the first example. However, because of the domain restrictions, we use indicator variables to select the pieces and transect segments that meet the criteria of the domains of interest.

Compute values at plot level

In the first example, we calculated $\overline{p}_h^{CWD}=0.9043$. The next task is to compute the estimated number of large pieces of CWD for each plot in the stratum, applying eq. 3.1. In this case, y_{hijmt} always is 1 (eq. 5, Table 3.1). δ_{hiimtd} is an indicator variable that takes the value of 1 if the piece of wood belongs to the domain (large-end diameter greater than 20 inches and in a Douglas-fir forest type condition class), and 0 otherwise. To calculate δ_{hiimtd}, we first assign each piece to a condition class, based on the slope distance from subplot center to the point of intersection of each piece (Table 7.2.3) and the transect segment beginning and ending slope distance (Table 7.2.2). Only pieces in the Douglas-fir forest type are included, that is, pieces in condition class 1 in plot 1, 2 in plot 2, and 1 in plot 3 (Table 7.2.1). Next, δ_{hiimtd} is assigned a value of 1 for the large pieces in this condition class. Eq. 3.1 can then be computed:

Plot 1:

$$y_{h1} = 43560\left[\frac{(\pi/2)}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t}\frac{\delta_{hijmtd}}{l_{hijmt}}\right] =$$

$$= 43560\left(\frac{(\pi/2)}{12*24*0.9043}\right)\left(\frac{0}{9}+\frac{1}{98}+\frac{1}{70}+\frac{1}{139}\right) = 8.32 \text{ pieces/acre}$$

Plot 2: $y_{h2} = 2.58 \text{ pieces/acre}$

Plot 3: $y_{h3} = 11.62 \text{ pieces/acre}$

The next step requires estimating the proportion of each plot's transect length in Douglas-fir forest type adjusted for partial plots outside the population (section 3.3.2). $\delta_{hijmkd'}$ is again a domain indicator that takes the value of 1 if a transect segment falls within the Douglas-fir forest type condition class, or 0 otherwise (Table 7.2.2). Then, eq. 3.20 is computed for each plot using the column labeled as $L_{hijmk}\delta_{hijmkd'}$:

Plot 1:

$$p_{h1d'} = \frac{1}{12L\overline{p}_h^{CWD}}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{k=1}^{K_{hijm}} L_{hijmk}\delta_{hijmkd'} =$$

$$= \frac{1}{12*24*0.9043}\left[(24+24+10.8)+(24+24+24)+(24+24+24)\right] = 0.7787$$

Plot 2 $p_{h2d'} = 0.2765$

Plot 3 $p_{h3d'} = 0.7883$

Computed stratum means, variances and covariance

The estimated strata means and variances for each of the two variables (number of large pieces and proportion of Douglas-fir forest type) are calculated as described in the first example, yielding:

	Stratum mean	Stratum variance
Number of large pieces per acre, $\overline{Y}_{hd}$	7.51	6.98
Proportion in Douglas-fir forest, $\overline{P}_{hd'}$	0.6145	0.0286

Estimating the variance of a ratio requires an estimate of the covariance between the two variables, following eq. 3.19:

$$\operatorname{cov}\left(\overline{Y}_{hd}, \overline{P}_{hd'}\right) = \frac{\sum_{i=1}^{n_h} y_{hid} p_{hid'} - n_h \overline{Y}_{hd} \overline{P}_{hd'}}{n_h\left(n_h - 1\right)} =$$

$$= \frac{\left(8.32 * 0.7787 + 2.58 * 0.2765 + 11.62 * 0.7883\right) - 3 * 7.51 * 0.6145}{3\left(3-1\right)} = 0.4193$$

Population totals

The total number of large pieces and acreage of Douglas-fir forest type are estimated following the process described in the first example, using data from Table 7.2.4:

	Total	Variance
Number of large pieces, $\hat{Y}_d$	3,236,354	$(1{,}062{,}388)^2$
Acreage of Douglas-fir forest, $\hat{A}_{d'}$ (acres)	367,443	$(104{,}102)^2$

Therefore, we estimate that there are approximately 3.2 million pieces of large CWD in Douglas-fir forest type, and that this forest type covers 367,400 acres.

The estimated population covariance is calculated from eq. 3.18 as:

$$\operatorname{cov}\left(\hat{Y}_d, \hat{A}_{d'}\right) = \frac{A_T}{n}\left[\sum_{h=1}^{H} W_h n_h \operatorname{cov}\left(\overline{Y}_{hd}, \overline{P}_{hd'}\right) + \sum_{h=1}^{H}\left(1 - W_h\right)\frac{n_h}{n}\operatorname{cov}\left(\overline{Y}_{hd}, \overline{P}_{hd'}\right)\right] = \left(285{,}152\right)^2$$

Estimated ratio and its variance

The final step is dividing the estimated total number of large pieces of CWD in the population by the estimated acreage of Douglas-fir forest (eq. 3.16):

$$\hat{R}_{dd'} = \frac{\hat{Y}_d}{\hat{A}_{d'}} = \frac{3{,}236{,}354}{364{,}443} = 8.81 \text{ pieces/acre}$$

with estimated variance (eq. 3.17):

$$\operatorname{var}\left(\hat{R}_{dd'}\right) = \frac{1}{\hat{A}_{d'}^2}\left[\operatorname{var}\left(\hat{Y}_d\right) + \hat{R}_{dd'}^2 \operatorname{var}\left(\hat{A}_{d'}\right) - 2\hat{R}_{dd'} \operatorname{cov}\left(\hat{Y}_d, \hat{A}_{d'}\right)\right] =$$

$$= \frac{1}{\left(367{,}443\right)^2}\left[\left(1{,}062{,}388\right)^2 + 8.81^2\left(104{,}102\right)^2 - 2 * 8.81\left(285{,}152\right)^2\right] = 9.28 \ \left(\text{pieces/acre}\right)^2$$

The standard error, estimated as the square root of the variance, is 3.05 pieces per acre. Assuming that the sampling distribution of the estimator can be approximated by a normal distribution, an approximate 95 percent confidence interval for the average number of large CWD pieces per acre of

Douglas-fir forest is 2.27 to 15.34 ($8.81 \pm t_{0.975,n-1} \times 3.05$, where $t_{0.975,n-1}$ is the 97.5 percentile of a *t*-distribution with *n*-1 = 14 degrees of freedom).

7.2.3. CWD Biomass in Individual Plot

In this example, we illustrate the estimation of the CWD biomass in accessible forest land in plot 1 (Table 7.2.3) using eq. 3.27. First, from Table 7.2.2 we estimate the length of transect in accessible forest land, denoted by condition class code 1. There are 58.38 ft of forest-land subplot 1, 72 ft in each of subplots 2 and 3, and none in subplot 4, for a total of 202.8 ft of transect in forest land.

The volume of each piece was calculated in the first example and is included in Table 7.2.3. There are no domain restrictions in the pieces because we are interested in the biomass of all CWD pieces present. Therefore, eq. 3.27 can be computed:

$$y_d = c\frac{\frac{\pi}{2}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{t} y_{jmt}\delta_{jmtd}/l_{jmt}}{\sum_{j=1}^{4}\sum_{m=1}^{3} L_{jmd'}} =$$

$$= \left(\frac{43560}{2000}\right)\left(\frac{\pi}{2}\right)\frac{\left(\frac{19.7}{9}+\frac{8889.6}{98}+\frac{1356.3}{70}+\frac{11029.6}{139}\right)}{202.8} = 32.33 \text{ tons/acre forest land}$$

Note the difference in the estimated CWD biomass for plot 1 in example 1 (25.17 tons per acre) and example 3 (32.33 tons per acre). In the first example, the objective was to estimate the total biomass in the population, which includes nonforest conditions. The amount of CWD biomass in nonforested conditions is 0 but those conditions actually are sampled. Further, in the first example, we needed to account for the portion of plots in the stratum that are not sampled. In this example, the interest is in describing what was found in the observed plot only, not the population. Therefore, only the condition of interest is included in the estimator as information from other plots in the population is not required. Users should be aware of this difference and interpret plot-level estimators accordingly.

Table 7.2.1. – Plot and condition class information in a stratum

Plot	Condition class	Land class	Forest type
1	1	Accessible forest land	Douglas-fir
1	2	Nonforest land	---
2	1	Accessible forest land	Red alder
2	2	Accessible forest land	Douglas-fir
3	1	Accessible forest land	Douglas-fir
3	2	Hazardous	---
4	------ Access denied by owner ------		

Table 7.2.2. – Transect segmentation data

Measured variables								Computed variables				
								Example 1			Example 2	
Plot	**Subplot**	**Transect**	**Segment**	**Condition class**	**Begin slope dist. (ft)**	**End slope dist. (ft)**	**Slope (%)**	**Segment length L_{hijmk} (ft)**	δ_{hijmk}	$L_{hijmk}\delta_{hijmk}$	$\delta_{hijmkd'}$	$L_{hijmk}\delta_{hijmkd'}$
1	1	30	1	1	0	32.3	90	24.0	1	24.0	1	24.0
1	1	150	1	1	0	31.5	85	24.0	1	24.0	1	24.0
1	1	270	1	1	0	11.0	20	10.8	1	10.8	1	10.8
1	1	270	2	2	11	24.5	20	13.2	1	13.2	0	0.0
1	2	30	1	1	0	31.5	85	24.0	1	24.0	1	24.0
1	2	150	1	1	0	29.3	70	24.0	1	24.0	1	24.0
1	2	270	1	1	0	24.5	20	24.0	1	24.0	1	24.0
1	3	30	1	1	0	27.4	55	24.0	1	24.0	1	24.0
1	3	150	1	1	0	25.4	35	24.0	1	24.0	1	24.0
1	3	270	1	1	0	24.0	0	24.0	1	24.0	1	24.0
1	4	30	1	2	0	28.0	60	24.0	1	24.0	0	0.0
1	4	150	1	2	0	27.4	55	24.0	1	24.0	0	0.0
1	4	270	1	2	0	24.1	10	24.0	1	24.0	0	0.0
2	1	30	1	1	0	24.5	20	24.0	1	24.0	0	0.0
2	1	150	1	1	0	24.1	10	24.0	1	24.0	0	0.0
2	1	270	1	1	0	24.5	20	24.0	1	24.0	0	0.0
2	2	30	1	2	0	24.3	15	24.0	1	24.0	1	24.0
2	2	150	1	2	0	24.3	15	24.0	1	24.0	1	24.0
2	2	270	1	2	0	24.5	20	24.0	1	24.0	1	24.0
2	3	30	1	1	0	26.8	50	24.0	1	24.0	0	0.0
2	3	150	1	1	0	24.1	10	24.0	1	24.0	0	0.0
2	3	270	1	1	0	25.8	40	24.0	1	24.0	0	0.0
2	4	30	1	1	0	24.5	20	24.0	1	24.0	0	0.0
2	4	150	1	1	0	24.1	10	24.0	1	24.0	0	0.0
2	4	270	1	1	0	24.5	20	24.0	1	24.0	0	0.0
3	1	30	1	1	0	28.0	60	24.0	1	24.0	1	24.0
3	1	150	1	1	0	24.0	0	24.0	1	24.0	1	24.0
3	1	270	1	1	0	14.3	40	13.3	1	13.3	1	13.3
3	1	270	2	2	14.3	---	---	10.7	0	0.0	0	0.0
3	2	30	1	2	---	---	---	24.0	0	0.0	0	0.0
3	2	150	1	2	---	---	---	24.0	0	0.0	0	0.0
3	2	270	1	2	---	---	---	24.0	0	0.0	0	0.0
3	3	30	1	1	0	25.1	30	24.0	1	24.0	1	24.0
3	3	150	1	1	0	24.3	15	24.0	1	24.0	1	24.0
3	3	270	1	1	0	28.6	65	24.0	1	24.0	1	24.0
3	4	30	1	1	0	24.1	10	24.0	1	24.0	1	24.0
3	4	150	1	1	0	24.0	0	24.0	1	24.0	1	24.0
3	4	270	1	1	0	28.0	60	24.0	1	24.0	1	24.0

Table 7.2.3. – Coarse woody debris piece data

Measured data										Calculated data (Example 1)		Calculated data (Example 2)	
Plot	Sub-plot	Transect	Slope distance (ft)	Species	Decay class	Transect diameter (in)	Small-end diameter (in)	Large-end diameter (in)	Length (ft)	Volume (ft^3)	Biomass (lb)	Cond. class	δ_{hijmtd}
1	1	30	15	Douglas-fir	2	3	3	5	9	0.83	19.7	1	0
1	2	30	20.4	Douglas-fir	1	28	20	28	98	316.43	8889.6	1	1
1	2	150	6.7	Douglas-fir	4	14	11	21	70	107.28	1356.3	1	1
1	3	30	12.2	Douglas-fir	2	33	12	33	139	467.39	11029.6	1	1
2	1	150	1.5	Red alder	4	7	6	7	4	0.93	9.0	1	0
2	1	270	9.9	Red alder	1	3	3	4	9	0.61	14.2	1	0
2	2	30	2.4	Red alder	3	4	3	4	10	0.68	7.1	1	0
2	2	30	4.8	Red alder	3	5	4	5	14	1.57	16.3	1	0
2	2	30	5.5	Red alder	3	7	3	7	48	7.59	78.9	1	0
2	2	30	7.6	Red alder	3	6	4	7	25	4.43	46.1	1	0
2	2	30	14.8	West. hemlock	3	4	3	4	7	0.48	8.9	1	0
2	2	150	4.5	Red alder	3	5	4	5	15	1.68	17.4	1	0
2	2	150	10.7	West. hemlock	2	6	3	6	15	1.84	40.5	1	0
2	2	150	23.9	West. hemlock	2	8	3	8	21	4.18	92.1	1	0
2	3	150	7.6	West. hemlock	4	6	8	9	10	3.95	46.7	2	0
2	3	150	20.5	West. hemlock	4	4	3	4	3	0.20	2.4	2	0
2	3	270	16.4	Douglas-fir	3	17	13	25	102	220.86	4405.4	2	1
2	3	270	20.5	Douglas-fir	3	8	7	11	19	8.81	175.7	2	0
3	1	30	10.3	Douglas-fir	3	11	3	18	87	79.01	1575.9	1	0
3	1	150	18.7	West. hemlock	2	9	5	10	48	16.36	360.4	1	0
3	3	30	6	Douglas-fir	4	20	13	30	44	128.27	1621.6	1	1
3	3	30	17.7	Red alder	4	3	3	5	16	1.48	14.4	1	0
3	3	150	6.2	Douglas-fir	3	28	24	33	87	395.03	7879.4	1	1
3	3	150	8.9	West. hemlock	2	6	6	7	11	2.55	56.2	1	0
3	3	150	17.3	Douglas-fir	2	20	15	25	100	231.80	5470.2	1	1
3	4	30	3.7	Unknown	5	20	---	---	21	45.81	579.2	1	---
3	4	30	18.2	Douglas-fir	4	15	17	18	32	53.49	676.3	1	0
3	4	150	22.3	West. Hemlock	2	4	3	4	4	0.27	6.0	1	0
3	4	270	12.6	Douglas-fir	3	3	3	4	6	0.41	8.2	1	0

Table 7.2.4. – Stratum data

Observed variables			Calculated variables							
				Example 1		Example 2				
				Biomass		Number of large pieces		Proportion in Douglas-fir forest		
Stratum	Area (acres)	Observed plots (n_h)	Proportion area in strata (W_h)	Mean (tons/acre)	Variance (tons/acre)²	Mean (pieces/acre)	Variance (pieces/acre)²	Mean	Variance	Covariance
1	403,200	3	0.2517	23.36	52.03	7.51	6.98	0.6145	0.0286	0.4193
2	470,400	5	0.2936	0.98	0.96	0.00	0.00	0.0000	0.0000	0.0000
3	728,400	7	0.4547	11.4	2.87	0.286	0.082	0.1643	0.0109	0.0279
Total	1,602,000	15								

Appendix 7.3. Bulk density (lbs/ft³) by tree species for the United States (USDA Forest Service 1999)

Species number	Genus	Species	Bulk density
10	Abies	spp.	21.22
11	Abies	amabilis	24.96
12	Abies	balsamea	21.22
14	Abies	bracteata	22.46
15	Abies	concolor	23.09
16	Abies	fraseri	21.22
17	Abies	grandis	21.84
19	Abies	lasiocarpa	19.34
20	Abies	magnifica	22.46
21	Abies	magnifica var. shastensis	22.46
22	Abies	procera	23.09
41	Chamaecyparis	lawsoniana	24.34
42	Chamaecyparis	nootkatensis	26.21
43	Chamaecyparis	thyoides	19.34
50	Cupressus	spp.	27.46
60	Juniperus	spp.	27.46
64	Juniperus	occidentalis	27.46
69	Juniperus	monosperma	28.08
70	Larix	spp.	27.46
71	Larix	laricina	30.58
72	Larix	lyallii	29.95
73	Larix	occidentalis	29.95
81	Calocedrus	decurrens	23.09
90	Picea	spp.	23.71
91	Picea	abies	23.71
92	Picea	breweriana	20.59
93	Picea	engelmannii	20.59
94	Picea	glauca	23.09
95	Picea	mariana	23.71
96	Picea	pungens	23.71
97	Picea	rubens	23.71
98	Picea	sitchensis	23.09
101	Pinus	albicaulis	23.09
102	Pinus	aristata	23.09
103	Pinus	attenuata	23.09
104	Pinus	balfouriana	23.09
105	Pinus	banksiana	24.96
106	Pinus	edulis	31.20
107	Pinus	clausa	28.70
108	Pinus	contorta	23.71
109	Pinus	coulteri	23.09

Species number	Genus	Species	Bulk density
476	Cercocarpus	montanus	62.40
479	Cercocarpus	intricatus	62.40
481	Cladrastis	lutea	32.45
490	Cornus	spp.	39.94
491	Cornus	florida	39.94
492	Cornus	nuttallii	36.19
500	Crataegus	spp.	38.69
510	Eucalyptus	spp.	41.81
521	Diospyros	virginiana	39.94
531	Fagus	grandifolia	34.94
540	Fraxinus	spp.	33.70
541	Fraxinus	americana	34.32
542	Fraxinus	latifolia	31.20
543	Fraxinus	nigra	28.08
544	Fraxinus	pennsylvanica	33.07
545	Fraxinus	profunda	33.70
546	Fraxinus	quadrangulata	33.07
551	Gleditsia	aquatica	37.44
552	Gleditsia	triacanthos	37.44
555	Gordonia	lasianthus	23.09
571	Gymnocladus	dioicus	31.20
580	Halesia	spp.	19.97
591	Ilex	opaca	31.20
600	Juglans	spp.	31.82
601	Juglans	cinerea	22.46
602	Julglans	nigra	31.82
611	Liquidambar	styraciflua	28.70
621	Liriodendron	tulipifera	24.96
631	Lithocarpus	densiflorus	36.19
641	Maclura	pomifera	47.42
650	Magnolia	spp.	28.08
660	Malus	spp.	38.06
680	Morus	spp.	36.82
681	Morus	alba	36.82
682	Morus	rubra	36.82
691	Nyssa	aquatica	28.70
692	Nyssa	ogeche	28.70
693	Nyssa	sylvatica	28.70
701	Ostrya	virginiana	39.31
711	Oxydendrum	arboreum	31.20
712	Paulownia	tomentosa	23.71

Appendix 7.3. (Continued)

Species number	Genus	Species	Bulk density	Species number	Genus	Species	Bulk density
110	Pinus	echinata	29.33	721	Persea	borbonia	31.82
111	Pinus	elliotti	33.70	731	Platanus	occidentalis	28.70
112	Pinus	engelmannii	23.09	740	Populus	spp.	23.09
113	Pinus	flexilis	23.09	741	Populus	balsamifera	19.34
114	Pinus	strobiformis	21.84	742	Populus	deltoides	23.09
115	Pinus	glabra	25.58	743	Populus	grandidentata	22.46
116	Pinus	jeffreyi	23.09	744	Populus	heterophylla	23.09
117	Pinus	lambertiana	21.22	745	Populus	deltoides	23.09
118	Pinus	leiophylla	23.09	745	Populus	sargentii	23.09
119	Pinus	monticola	21.84	746	Populus	tremuloides	21.84
120	Pinus	muricata	23.09	747	Populus	balsamifera	19.34
121	Pinus	palustris	33.70	748	Populus	fremontii	21.22
122	Pinus	ponderosa	23.71	749	Populus	angustifolia	21.22
123	Pinus	pungens	30.58	752	Populus	alba	23.09
124	Pinus	radiata	23.09	755	Prosopis	spp.	36.19
125	Pinus	resinosa	25.58	760	Prunus	spp.	29.33
126	Pinus	rigida	29.33	761	Prunus	pensylvanica	22.46
127	Pinus	sabiniana	23.09	762	Prunus	serotina	29.33
128	Pinus	serotina	31.82	763	Prunus	virginiana	22.46
129	Pinus	strobus	21.22	765	Prunus	nigra	29.33
130	Pinus	sylvestris	25.58	766	Prunus	americana	29.33
131	Pinus	taeda	29.33	800	Quercus	spp.	36.19
132	Pinus	virginiana	28.08	801	Quercus	agrifolia	43.68
133	Pinus	monophylla	31.20	802	Quercus	alba	37.44
133	Pinus	nigra	25.58	803	Quercus	arizonica, grisea	43.68
134	Pinus	discolor	31.20	804	Quercus	bicolor	39.94
135	Pinus	arizonica	23.09	805	Quercus	chrysolepis	43.68
202	Pseudotsuga	menziesii	28.08	806	Quercus	coccinea	37.44
211	Sequoia	sempervirens	21.22	807	Quercus	douglasii	31.82
212	Sequoiadendron	giganteum	21.22	808	Quercus	durandii	37.44
221	Taxodium	distichum var. nutans	26.21	809	Quercus	ellipsoidalis	34.94
231	Taxus	brevifolia	37.44	810	Quercus	emoryi	43.68
241	Thuja	occidentalis	18.10	811	Quercus	engelmannii	43.68
242	Thuja	plicata	19.34	812	Quercus	falcata var. falcata	32.45
251	Torreya	californica	21.22	813	Quercus	falcata var. pagodaefolia	38.06
260	Tsuga	spp.	23.71	814	Quercus	gambelii	39.94
263	Tsuga	heterophylla	26.21	815	Quercus	garryana	39.94
264	Tsuga	mertensiana	26.21	816	Quercus	ilicifolia	34.94
299		softwood	23.71	817	Quercus	imbricaria	34.94
300	Acacia	spp.	37.44	818	Quercus	kelloggii	31.82
310	Acer	spp.	30.58	819	Quercus	laevis	32.45

Appendix 7.3. (Continued)

Species number	Genus	Species	Bulk density	Species number	Genus	Species	Bulk density
311	Acer	barbatum	33.70	820	Quercus	laurifolia	34.94
312	Acer	macrophyllum	27.46	821	Quercus	lobata	39.94
313	Acer	negundo	27.46	822	Quercus	lyrata	35.57
314	Acer	nigrum	32.45	823	Quercus	macrocarpa	36.19
315	Acer	pensylvanicum	27.46	824	Quercus	marilandica	34.94
316	Acer	rubrum	30.58	825	Quercus	michauxii	37.44
317	Acer	saccharinum	27.46	826	Quercus	muehlenbergii	37.44
318	Acer	saccharum	34.94	827	Quercus	nigra	34.94
319	Acer	spicatum	27.46	828	Quercus	nuttalli	34.94
321	Acer	glabrum	27.46	829	Quercus	oblongifolia	43.68
322	Acer	grandidentatum	27.46	830	Quercus	palustris	36.19
330	Aesculus	californica	23.71	831	Quercus	phellos	34.94
330	Aesculus	spp.	20.59	832	Quercus	prinus	35.57
341	Ailanthus	altissima	23.09	833	Quercus	rubra	34.94
350	Alnus	spp.	23.09	834	Quercus	shumardii	34.94
355	Amelanchier	spp.	41.18	835	Quercus	stellata	37.44
361	Arbutus	menziesii	36.19	837	Quercus	velutina	34.94
367	Asimina	triloba	29.33	838	Quercus	virginiana	49.92
370	Betula	spp.	29.95	839	Quercus	wislizeni	43.68
371	Betula	alleghaniensis	34.32	840	Quercus	incana	34.94
372	Betula	lenta	37.44	843	Quercus	hypoleucoides	43.68
373	Betula	nigra	34.94	901	Robinia	pseudoacacia	41.18
374	Betula	occidentalis	33.07	902	Robinia	neomexicana	41.18
375	Betula	papyrifera	29.95	920	Salix	spp.	22.46
376	Betula	papyrifera var. commutata	29.95	925	Sapium	sebiferum	29.33
379	Betula	populifolia	28.08	931	Sassafras	albidum	26.21
381	Bumelia	lanuginosa	29.33	935	Sorbus	americana	26.21
391	Carpinus	caroliniana	36.19	945	Tamarix	spp.	24.96
400	Carya	spp.	38.69	950	Tilia	spp.	19.97
401	Carya	aquatica	38.06	951	Tilia	americana	19.97
402	Carya	cordiformis	37.44	952	Tilia	heterophylla	19.97
403	Carya	glabra	41.18	970	Ulmus	spp.	31.20
404	Carya	illinoensis	37.44	971	Ulmus	alata	35.57
405	Carya	laciniosa	38.69	972	Ulmus	americana	28.70
406	Carya	myristicaeformis	34.94	973	Ulmus	crassifolia	35.57
407	Carya	ovata	39.94	974	Ulmus	pumila	28.70
408	Carya	texana	33.70	975	Ulmus	rubra	29.95
409	Carya	tomentosa	39.94	976	Ulmus	serotina	35.57
421	Castanea	dentata	24.96	977	Ulmus	thomasii	35.57
422	Castanea	pumila	24.96	980	Aleurites	fordii	29.33
423	Castanea	ozarkensis	24.96	981	Umbellularia	californica	31.82

Appendix 7.3. (Continued)

Species number	Genus	Species	Bulk density
430	Castanopsis	spp.	26.21
450	Catalpa	spp.	23.71
460	Celtis	spp.	30.58
461	Celtis	laevigata	29.33
462	Celtis	occidentalis	30.58
471	Cercis	canadensis	36.19
475	Cercocarpus	ledifolius	62.40

Species number	Genus	Species	Bulk density
981	Vaccinium	arboreum	29.33
983	Melia	azedarach	29.33
984	Planera	aquatica	33.07
985	Cotinus	obovaus	29.33
990	Olneya	tesota	62.40
998		hardwood	31.82
999		unknown	28.70

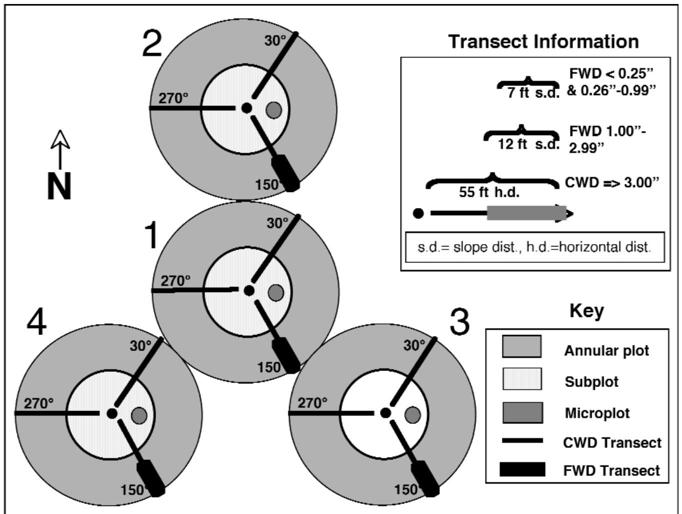
Appendix 7.4. Estimation constants of fine woody debris, litter, and duff by forest-type group

Forest-type group code	Forest Type Group	Fine Woody Debris (squared diameter, inches)			FWD and slash bulk density (lbs/ft³)	Litter bulk density (lbs/ft³)	Duff bulk density (lbs/ft³)
		Small	Medium	Large			
100	White/red/jack pine	0.017	0.254	3.043	23.71	5.14	13.21
120	Spruce/fir	0.018	0.256	3.058	22.46	1.85	4.76
140	Longleaf/slash pine	0.020	0.310	3.457	33.70	5.14	13.21
160	Loblolly/shortleaf pine	0.019	0.286	3.279	29.33	5.33	13.72
180	Pinyon/juniper	0.018	0.257	3.062	28.70	3.34	8.59
200	Douglas-fir	0.016	0.233	2.879	28.80	1.85	4.76
220	Ponderosa pine	0.019	0.293	3.330	23.09	3.34	8.59
240	Western white pine	0.018	0.262	3.101	21.84	3.34	8.59
260	Fir/spruce/mountain hemlock	0.017	0.247	2.987	22.46	1.85	4.76
280	Lodgepole pine	0.017	0.248	2.993	23.71	3.34	8.59
300	Hemlock/Sitka spruce	0.018	0.258	3.072	26.21	1.85	4.76
320	Western larch	0.018	0.272	3.175	29.95	3.34	8.59
340	Redwood	0.018	0.267	3.141	21.22	3.34	8.59
360	Other western softwoods	0.019	0.277	3.210	24.34	3.34	8.59
370	California mixed conifer	0.018	0.271	3.172	24.34	3.34	8.59
380	Exotic softwoods	0.018	0.262	3.101	31.20	3.34	8.59
400	Oak/pine	0.019	0.280	3.238	37.44	5.24	13.48
500	Oak/hickory	0.018	0.272	3.179	28.70	4.47	11.51
600	Oak/gum/cypress	0.019	0.286	3.282	32.45	4.46	11.46
700	Elm/ash/cottonwood	0.019	0.280	3.238	33.07	3.06	7.87
800	Maple/beech/birch	0.018	0.265	3.124	23.09	4.37	11.24
900	Aspen/birch	0.019	0.279	3.226	23.09	4.77	12.27
910	Alder/maple	0.018	0.274	3.192	23.09	4.37	11.24
920	Western oak	0.017	0.249	3.005	31.82	4.47	11.51
940	Tanoak/laurel	0.017	0.247	2.986	39.31	4.47	11.51
950	Other western hwds	0.015	0.206	2.661	39.31	4.47	11.51
980	Tropical hardwoods	0.018	0.262	3.101	31.20	4.40	11.31
990	Exotic hardwoods	0.018	0.262	3.101	31.20	4.40	11.31
999	Nonstocked	0.018	0.262	3.101	28.08	4.41	11.33

Note: All constants are subject to revisions as additional information is available. Users are strongly cautioned to use their own local-regional values where available. FWD constants are based on Woodall and Monleon (in press); FWD and slash bulk density are based on averaging the bulk densities of individual species in each forest-type group (see Appendix 7.3); duff/litter constants are based on bulk densities measured by FIA's phase 3 soils inventory (O'Neill et al. 2005a) and will be updated as future information is available.

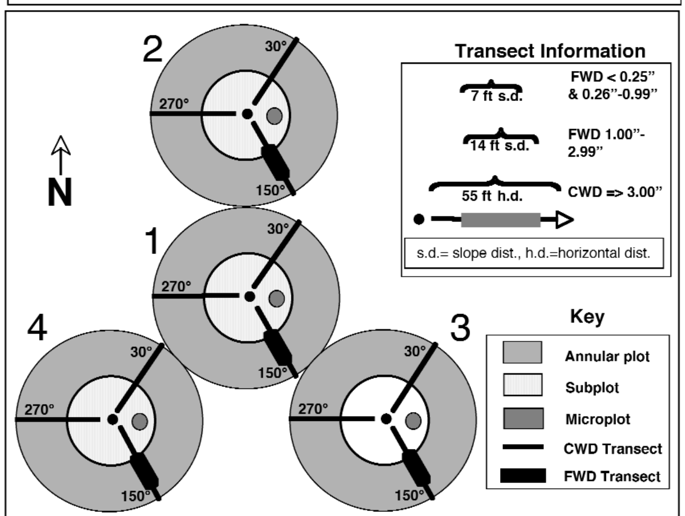
Appendix 7.5 Down Woody Material Sample Designs, 1999-2001

A



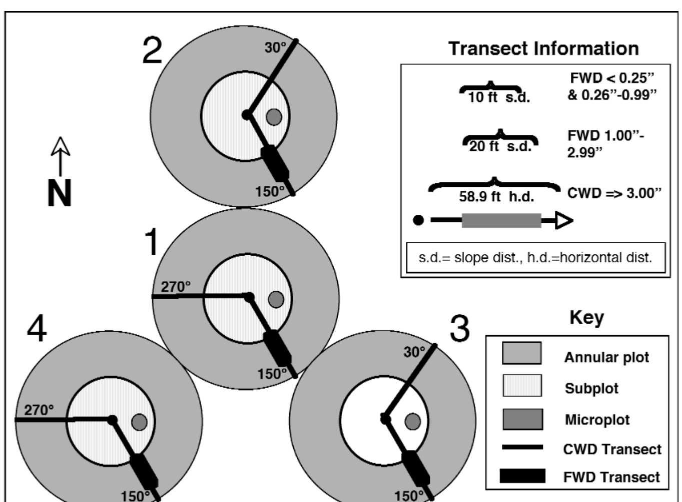
Distances between subplots (2, 3, and 4) and subplot center (1): 120 ft., at angles (deg) 150, 210, and 270 respectively; distance from sub-plot center to microplot center: 12 ft.

B



Distances between subplots (2, 3, and 4) and subplot center (1): 120 ft, at angles (deg) 150, 210, and 270 respectively; distance from sub-plot center to microplot center: 12 ft.

C



Dist. between subplots (2, 3, and 4) and subplot center (1): 120 ft at angles (deg.) 0, 120, & 240 respectively; dist. from subplot center to microplot center: 12 ft; shrubs/herbs sampled on microplot. Duff/litter sampled at 14 & 24 ft s.d. on each CWD transect.

Appendix 7.6 Down Woody Material field datasheet

Transect Segment Data

Sub plot xx	Transect xxx	Condition x	Dist Start xxx.y (ft)	Dist End xxx.y (ft)	Slope xxx (%)

Duff, Litter and Fuelbed Depths

Transect	Sampled x	Duff xx.y (in)	Litter xx.y (in)	Fuelbed xx.y (ft)
1 30				
1 150				
1 270				
2 30				
2 150				
2 270				
3 30				
3 150				
3 270				
4 30				
4 150				
4 270				

CWD Form

Sub Plot xx	Transect xxx	Dist xx.y (ft)	Species xxx	Tran. Dia xxx (in)	Sm. End xxx (in)	Lg. End xxx (in)	Length xxx (ft)	Decay x	Hollow x	History x

FWD Form

Sub Plot	Condition x	0.00 - .25 Small xxx	.25 - 1.00 Med xxx	1.00 - 3.00 Large xxx	H. Count Reason x	Residue Pile x
1						
2						
3						
4						

History		Microplot Cover	
1	Natural	0	None
2	<=15 yrs.	1	Trace
3	>15 yrs.	10	1-10
4	Firewood	20	11 - 20
5	Unknown	99	91 - 100

Microplot Fuel Loading

Sub Plot	Live Shrub xx (%)	Height xx.y (ft)	Dead Shrub xx (%)	Height xx.y (ft)	Live Herb xx (%)	Height xx.y (ft)	Dead Herb xx (%)	Height xx.y (ft)	Litter % xx (%)
1									
2									
3									
4									

Residue Pile

Sub Plot xx	Condition xx (%)	Azimuth xxx (deg)	Shape x	Length 1 xx (ft)	Length 2 xx (ft)	Width 1 xx (ft)	Width 2 xx (ft)	Height 1 xx (ft)	Height 2 xx (ft)	Density xx (%)

Woodall, Christopher W.; Monleon, Vicente J. 2008. **Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program.** Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

The USDA Forest Service's Forest Inventory and Analysis program conducts an inventory of forests of the United States including down woody materials (DWM). In this report we provide the rationale and context for a national inventory of DWM, describe the components sampled, discuss the sampling protocol used and corresponding estimation procedures, and provide guidance on managing and processing DWM data and incorporating that information into inventory analysis and research projects.

KEY WORDS: down woody material, forest inventory, line-intersect sampling, coarse woody debris, fine woody debris

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