Carbon Accounting and Management of Lying Dead Wood

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Executive Summary

Lying dead wood (LDW), the dead trees and limbs on the forest floor, has a range of important ecological functions, including carbon storage. This report explores the details of carbon storage in LDW as it relates to projects that seek to increase carbon storage on forestland. The first chapter of this report reviews the characteristics and quantity of the carbon stored in LDW throughout the U.S. Because quantities and characteristics of LDW carbon stocks are influenced by ecoregion, we highlight the differences and similarities between seven major forest types of the U.S. Similarly, we discuss the influence of stand development stage, disturbance, and management on LDW.

Chapter 2 delves into the measurement of LDW. First, we discuss general methodological and statistical issues of measuring and estimating LDW amount. Measuring LDW is more challenging than inventorying standing trees, because breakage and decay make LDW even more irregular and heterogeneous than living trees. Our discussion addresses six features of LDW that make an efficient inventory challenging:

- Rarity and clumpiness of LDW
- Difficulties in allocating sample points effciently
- Boundary slopover issues
- Visibility issues
- Measurement accuracy challenges
- Problems in assigning decay classes

We discuss the following seven categories of LDW measurement methods, their required measurements, special advantages, and operational challenges and sources of bias:

- Fixed area plots
- Line intersect sampling
- Transect relascope sampling
- Point relascope sampling
- Prism sweep method (diameter relascope sampling)
- Perpendicular distance sampling
- Line intersect distance sampling

In Section 9, we address the comparison of implementation costs. Since there are only a small number of cost or time estimates for LDW measurement, those planning an LDW inventory should conduct a pilot study to estimate costs before embarking on a full campaign.

Conclusions

LDW is an important pool of carbon throughout the U.S., ranging from about 2 t/ac to 10 t/ac of biomass (3.2 to 16.9 MT of CO_2eq/ac). On average, LDW makes up from 1.7% to 4.6% of total forest carbon, though in individual stands the percentage can be higher. Both the quantity of LDW and the percentage of total forest carbon it represents vary significantly between regions and forest types, so LDW retention requirements should also vary by forest type. Though carbon storage in LDW is important, the other values that LDW provides, such as wildlife habitat, erosion protection, water storage, and nutrient cycling, may be even more important. While other forest structures (e.g., live trees) could sequester additional carbon in the absence of LDW, there are no replacements for these other values.

The in-depth discussion of sampling methods of Chapter 2 shows that there is no perfect method for sampling LDW. The extensive list of references for both sampling methods and LDW characteristics by forest type provides the most comprehensive resource to date for planning an LDW inventory. Inventories of LDW or assessment of the impact of management on LDW should be based on the characteristics of LDW for the particular forest type. The particularities of forest type, site conditions, and inventory goals determine the best sampling methodology.

Management effects on LDW carbon are complex and must be considered within the context of natural cycles of LDW change. For example, forest management decisions that remove small pieces of LDW will have a more transient effect on LDW carbon than decisions that remove large pieces of LDW, because large pieces take longer to decay and are only available in stands with mature or old trees. In general, uneven-aged management can maintain significantly more LDW than even-aged systems; however, any silvicultural system appropriate to the forest type can be adapted to promote maintenance of the LDW carbon pool. Preservation and recruitment of standing dead trees, particularly large dead trees, is important to maintaining LDW because they are the source for future LDW. Where disturbances, notably fire, may reduce the LDW carbon pool, management strategies should focus on maintaining large pieces of LDW that are unlikely to be completely consumed and will remain on-site for decades.

Forest projects designed to increase carbon storage under the Climate Action Reserve's Forest Project Protocol are unlikely to have a negative impact on long-term LDW. Forest projects are usually employ uneven-aged silvicultural practices, and the main eligible management activities for these projects are, on balance, likely to increase LDW carbon. It is also unlikely that increased LDW retention will cause a shift of harvesting activities to other forestlands (i.e., leakage), because of the low value of trees that become LDW. However, LDW retention may increase forest management costs in other ways that deserve further research.

Background

This report was commissioned by the Climate Action Reserve as part of their continuing efforts to provide regulatory-quality standards for the development, quantification, and verification of greenhouse gas (GHG) emissions reduction projects in North America. One of these standards, the Forest Project Protocol (FPP), provides requirements and guidance for quantifying sequestration of carbon on forestland. The FPP allows projects to account for changes in all forest carbon pools, but some pools are optional. Soil carbon, litter, shrubs and herbaceous understory, and LDW have all been optional pools because of the assessment that the likelihood of significant changes in these pools is low and of the difficulty of accurately and cost effectively quantifying such changes over time. The Reserve's definitions of other forest carbon pools are available in the FPP on line at www.climateactionreserve.org/how/protocols/adopted/forest/current/.

FPP accounting does include snags (i.e., standing dead trees), under the assumption that all LDW originates as standing dead wood, and snags can be included in common-practice forest inventory sampling practices. In addition, the FPP encourages retention of LDW because of its important ecological role. Currently, as part of the FPP's requirements for natural forest management, projects must ensure that LDW is retained in sufficient quantities, i.e., commensurate with recruitment from snags. In addition, projects must maintain standing dead trees equal to 1 MT of CO_2eq/ac or 1% of standing live carbon stocks.

This report is designed to advance the discussion of carbon accounting and management of LDW. The goal is to synthesize the current scientific literature related to the magnitude of carbon in lying dead wood for different forest types and to review options for quantifying carbon stocks in LDW. The results will help test the assumption that the impact of forest projects on the LDW carbon pool is likely to be small. It is important to reexamine the role of LDW for two reasons. First, this reexamination is part of the Reserve's process of making improvements to the FPP's clarity, accuracy, environmental integrity, and cost-effectiveness. Second, interest in LDW has grown because of expanding use of forest biomass for energy.

Chapter 1: Magnitude, Characteristics, and Carbon of Lying Dead Wood in the U.S.

1. Introduction

Lying dead wood (LDW), the dead trees and limbs on the forest floor, has an essential ecological role, part of which is the storage of carbon. The first chapter of this report reviews the characteristics and quantities of the carbon stored in LDW throughout the U.S. Because quantities and characteristics of LDW carbon stocks are influenced by ecoregion, we highlight the differences and similarities between the forest types of the U.S. Similarly, we discuss the influence of stand development stage, disturbance, and management on LDW.

1a. Ecological and Other Roles of LDW

LDW has other values in addition to its role in carbon storage. For example, LDW is an important element of wildlife habitat in forests (Harmon et al. 1986, Freedman et al. 1996). Many forest-floor vertebrates benefit from or depend on LDW (Butts and McComb 2000). In the Southeastern U.S., more than 55 mammal species, more than 20 bird species, and many reptiles and amphibian species rely on dead wood for habitat (Lanham and Guynn 1996, Loeb 1996, Whiles and Grubaugh 1996); the numbers are similar for the forests of the Pacific Northwest (Carey and Johnson 1995, McComb 2003) and the Northeast (DeGraaf et al. 1992). In aquatic environments, LDW acts as a critical component of habitat by ponding water, aerating streams, storing sediments, and providing crucial refuge from predation (Angermeier and Karr 1984, Everett and Ruiz 1993, Gurnell et al. 1995, Mellina and Hinch 2009, Sass 2009). LDW and other types of dead wood are key elements in maintaining habitat for saproxylic insects (Grove 2002, Gunnarsson et al. 2004). LDW serves as a seedbed for tree and plant species and can be beneficial to seedling regeneration after harvest (Grisez 1960, McInnis and Roberts 1994, McGee 2001, Ripple and Larsen 2001, Weaver et al. 2009). Fungi, mosses, and liverworts depend on dead wood for nutrients and moisture; in turn, many trees rely on mutualistic relationships with ectomycorrhizal fungi (Hagan and Grove 1999, Åström et al. 2005).

LDW also plays an important physical role in forests and riparian systems. LDW can provide erosion protection by reducing overland flow (McIver and Starr 2001, Jia-bing et al. 2005). LDW also has substantial water-holding capacity (Fraver et al. 2002). In riparian systems, LDW provides sites for vegetation colonization, forest island growth and coalescence, sediment metering, and forest floodplain development (Fetherston et al. 1995).

In some ecosystems, LDW is a long-term source of nutrients (Harmon et al. 1986, Johnson and Curtis 2001, Greenberg 2002, Mahendrappa et al. 2006) and is an important contributor to soil organic material (Graham and Cromack Jr. 1982, Harvey et al. 1987). Although LDW is often low in nitrogen itself, nitrogen fixation in LDW is an important source of this limiting nutrient in both terrestrial and aquatic ecosystems (Roskoski 1980, Harmon et al. 1986, Son 2001).

Another issue related to LDW is the use of forest biomass for energy and fuel, which has a direct impact on quantities and characteristics of LDW. Use of forest biomass for energy is the subject of both political debate and scientific research (Evans and Finkral 2009, Richter Jr. et al. 2009). A key, still-unsettled element of this debate is the carbon impact of using forest biomass for

energy or fuel (Eriksson and Gustavsson 2010, Jones et al. 2010). Expanding use of forest biomass for energy and intensification of harvests has resulted in calls for assurances of sustainability (Evans et al. 2010, Janowiak and Webster 2010). These calls for sustainable forest biomass harvesting are based on the key ecological roles that LDW and other forest structures affected by biomass harvesting play in forest ecosystems.

2. Methods

2a. What's in a Name?

As trees die or drop their branches on the forest floor, their nomenclature becomes more complex. Many different names are used in the scientific literature and common parlance for dead wood on the forest floor. In some cases, differences in names reflect important details about size or condition. In other cases, the use of terms has changed to reflect changing attitudes towards dead wood. Traditionally referred to as "debris," dead wood is now valued for the nutrients it holds, the wildlife habitat it provides, and even the aesthetic qualities it adds to the forest. Hence, more recent publications refer to it as "downed woody material."

This report focuses on LDW as defined by the Climate Action Reserve:

> *Any piece(s) of dead woody material from a tree, e.g., dead boles, limbs, and large root masses, on the ground in forest stands. Lying dead wood is all dead tree material with a minimum average diameter of 5" and a minimum length of 8'. Anything not meeting the measurement criteria for lying dead wood will be considered litter. Stumps are not considered lying dead wood.*

The Reserve's definition of LDW is similar to the U.S. Forest Service (USFS) definition of coarse woody debris (CWD), which is defined as down dead wood with a small-end diameter of at least 3" and a length of at least 3' (Woodall and Monleon 2008). Measurements taken using the USFS definition will include more material than measurements taken using the Reserve's definition because the USFS definition includes smaller pieces. While LDW may focus on larger pieces and "coarse woody material" may have less of a negative connotation, CWD is the most common term used in scientific research. For example, a search of ISI Web of Knowledge, a primary academic search engine, yielded 1,625 scientific papers that mention CWD and only 46 that mention LDW (Figure 1). Therefore, much of the research discussed in this review measured or described CWD; we treat it as synonymous with LDW though Chapter 2 discusses the implications of differences in definitions of CWD and LDW.

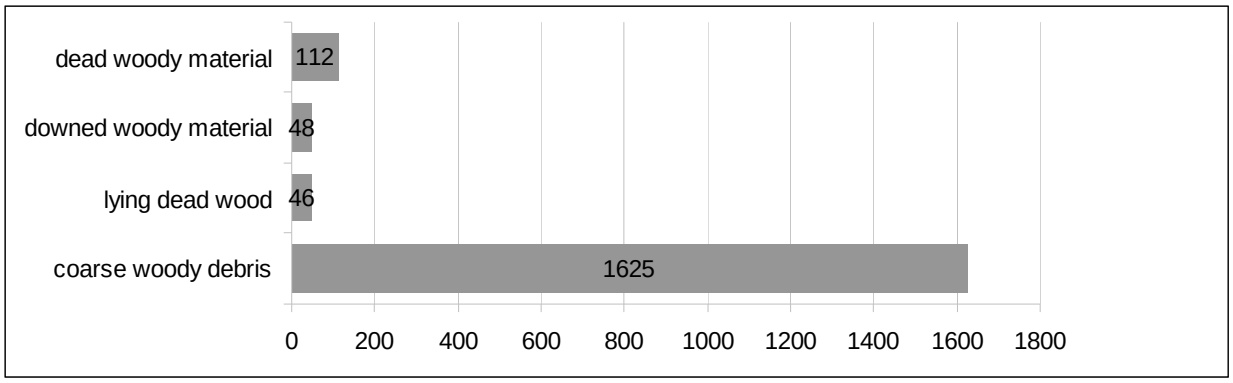

Figure 1 Search results from ISI Web of Knowledge

2b. Units of Measure for Lying Dead Wood

As discussed in detail in Chapter 2, there are many ways of measuring LDW. There are also different measurable attributes of LDW, such as mass, volume, number of pieces, and piece decomposition. Some measures of dead wood focus on its role as a fuel for fire and establish size by fuel-hour class (which is determined by the time it takes a piece of wood to dry out after being completely wet; Table 1).

Table 1 Conversion from fuel-hour class to piece size (Woodall and Williams 2005)

Transect diameter (in.)	Class name	Fuel-hour class (hr)
0.00–0.24	Small fine woody material	1
0.25–0.99	Medium fine woody material	10
1.00–2.99	Large fine woody material	100
3.00+	Lying dead wood	1,000+

The fact that researchers choose to measure mass, volume, or other attributes of LDW based on the particular focus of their study makes meta-analysis more challenging. To the extent possible, this review reports the mass of LDW biomass in English tons per acre (t/ac) and its carbon dioxide (CO_2eq) equivalent in metric tons per acre (MT of CO_2eq/ac), which is the standard report unit for Climate Action Reserve projects. English tons per acre are easily converted to metric tons per hectare by multiplying by 2.24. In general, estimates of LDW mass have been converted to estimates of carbon using average conversion factors of 0.521 for softwoods and 0.491 for hardwoods (Birdsey 1992, Waddell 2002) and from carbon to CO_2 equivalent by multiplying by the ratio of the atomic mass of a CO_2 molecule to the atomic mass of a carbon atom, 44:12 (Environmental Protection Agency 2005a, b). We used site- or species-specific conversion factors for the carbon content of wood if they were available. Similarly, volume estimates have been converted to mass using bulk density estimates of 0.012 t/ft^3 for softwoods and 0.016 t/ft^3 for hardwoods, or species-specific estimates of bulk density where possible (US Forest Service 1999, Woodall and Monleon 2008). For practitioners not accustomed to measuring the mass of LDW, the Natural Fuels Photo Series illustrates various levels of LDW and can be useful in visualizing LDW quantities (http://depts.washington.edu/nwfire/dps/; see "Loading (t/ac)" in the "Woody Material" section).

3. *Processes That Drive LDW*

3a. Stand Development and LDW


Zander Evans

The process of dead wood accumulation in a forest stand consists of the shift from live tree to snag to LDW (unless a disturbance has felled live trees, shifting them directly to LDW as discussed in Section 3c). In general, stands have the most LDW either when they are young or when they are old. Vigorous stands at intermediate stages of development tend to have less LDW. The pattern of LDW accumulation over time is often referred to as U-shaped (Harmon et al. 1986, Sturtevant et al. 1997, Feller 2003, Martin et al. 2005, Brassard and Chen 2008). Large quantities of LDW are usually present at stand initiation as legacies of the previous stand. These legacies decompose as the stand ages and new LDW is generated as trees and branches in the new stand die. The trough of the U-shaped pattern in intermediate-aged stands occurs when legacies from the previous stand have decayed but the stand is still too young to experience much self-thinning or other causes of tree mortality. The stem exclusion phase of stand development, during which the competition between trees for resources results in significant mortality (Oliver and Larson 1996), creates a new pulse of LDW as stands age. Tree size and the sizes of individual pieces of LDW also increase as trees age. The slower decomposition of these larger pieces and increased mortality can combine to create a second peak of LDW in old forests. Accumulation of LDW in old stands is determined by site productivity, decomposition rates, and disturbances.

3b. Decomposition

Physical breakdown and biological decomposition remove LDW from forests over time (Harmon et al. 1986). The diameter of each piece, temperature of the site, amount of precipitation, and tree species all influence the rate of LDW decomposition (Zell et al. 2009). In general, conifers decay more slowly than deciduous species (Zell et al. 2009). Other factors that encourage decomposition include warmer temperatures, rainfall between 43 and 51 in/year (1,100 and 1,300 mm/year), and small-sized pieces (Zell et al. 2009). While there is great variation across ecosystems and individual pieces of LDW, log fragmentation generally appears to occur over 25 to 85 years in the U.S. (Harmon et al. 1986, Ganjegunte et al. 2004, Yamasaki and Leak 2006, Campbell and Laroque 2007).

3c. Effects of Disturbance on LDW

Natural disturbances such as wind events, ice storms, and insect outbreaks add to the LDW pool. Hurricanes and other wind storms can increase the mass of LDW by almost eight times (Krauss et al. 2005, Busing et al. 2009, Cromer et al. 2009). Ice storms can have similar effects (Rebertus

et al. 1997, McCarthy et al. 2006). Insect outbreaks can create significant additions to the LDW pool. For example, Eastern spruce budworm (*Choristoneura fumiferana*) defoliation can generate twice the LDW volume of a clearcut harvest (Payer and Harrison 2000), while mountain pine beetle (*Dendroctonus ponderosae*) can create a fourfold increase in LDW (Klutsch et al. 2009). Non-native insects have the potential to alter natural cycles and patterns of LDW accumulation (McGee 2000, Gandhi and Herms 2010).

Unlike most other disturbances, fire has the potential to either increase the amount of LDW (by killing trees) or reduce the amount of LDW (by burning away existing LDW). In most fires there is a combination of both processes, so the overall impact of fire on LDW is complex. Fire consumes more LDW when it burns during drier parts of the fire season and when the LDW is more decomposed (Skinner 1999). A key distinction in fire effects on LDW can be drawn between forests that experience frequent, low-intensity fires and those that experience long-interval, high-severity fires (Stephens et al. 2007). For example, fire in lodgepole pine (*Pinus contorta*) forests, a high-severity fire regime, removed 16% of the LDW (Tinker and Knight 2000), while prescribed fire in a low-intensity Southeast pine forest did not significantly change LDW in comparison to unburned plots (Kilpatrick et al. 2010). Section 4 addresses the nuances of fire regime effect on LDW for each forest type.

3d. Management and LDW

As with fire, the effect of forest management varies with the ecosystem and the type of activity. Many harvests increase LDW because tops, limbs, small trees, or cull trees (i.e., slash) are left on-site as a byproduct of removing more economically valuable material (e.g., saw timber). For example, even a 10% basal-area removal in the Acadian forest of Maine significantly increased the volume and mass of LDW (Fraver et al. 2002). However, over the long term managed forests often have less LDW than unmanaged stands (Lesica et al. 1991, Duvall and Grigal 1999, Briggs et al. 2000, Gibb et al. 2005, Lõhmus and Lõhmus 2005). Harvests can also change the distribution of decay classes of LDW and reduce the average piece size of LDW (Fraver et al. 2002, Stevenson et al. 2006). These effects of management are discussed in detail in Section 4.

In some harvests, there is an economic incentive to remove the slash from the site. For example, harvests that supply woody biomass for energy production can include previously unmerchantable material (Evans and Finkral 2009, Benjamin et al. 2010). Another class of harvest that may reduce LDW on-site is fuel reduction. Since the objective in fuel reduction treatments is to reduce the amount of flammable material on-site, such treatments are likely to reduce LDW whether they employ mechanical thinning, prescribed fire, or both (Knapp et al. 2005, Stephens and Moghaddas 2005, Kilpatrick et al. 2010). Some silvicultural prescriptions call for site preparation, e.g., piling, windrowing, or scalping to expose mineral soil, and such treatments can reduce LDW over large areas (Robichaud and Waldrop 1994, Jurgensen et al. 1997).

3e. National Assessments of LDW

International treaties on carbon and climate change have driven nations to take stock of the carbon stored in LDW and other forest carbon pools. However, many national forest inventories

avoid measuring dead wood because it is seen as time consuming (Rondeux and Sanchez 2010). National overviews provide context for the forest-type level review in Section 4. For example a review of LDW in Russia revealed that Western Russia has lower LDW stocks (1.8 to 2.6 t/ac; 2.9 to 4.2 MT of CO_2eq/ac) than in the East Siberian and Far Eastern regions (4.9 to 6.4 t/ac; 8.0 to 10.5 MT of CO_2eq/ac (Krankina et al. 2002). Average estimates of LDW in Australian native forests included 8.4 t/ac (13.8 MT of CO_2eq/ac) in woodlands, 22.5 t/ac in open forests (36.8 MT of CO_2eq/ac), and 59.8 t/ac (99.5 MT of CO_2eq/ac) in tall open forests (Woldendorp and Keenan 2005).

Ranges of LDW in the U.S. are similar. For example, an influential review identified the range of LDW as 4.9 to 17 t/ac (8 to 27.7 MT of CO_2eq/ac) in deciduous forests and 4.5 to 228 t/ac (7.7 to 395 MT of CO_2eq/ac) for coniferous forests (Harmon et al. 1986). More recent national overviews of LDW have taken advantage of USFS Forest Inventory and Analysis (USFS FIA) data to generate estimates by region. Figure 2 shows estimates for forested climatic regions, which range from 0.4 to 6.3 t/ac (0.7 to 11 MT of CO_2eq/ac) (Woodall and Liknes 2008).

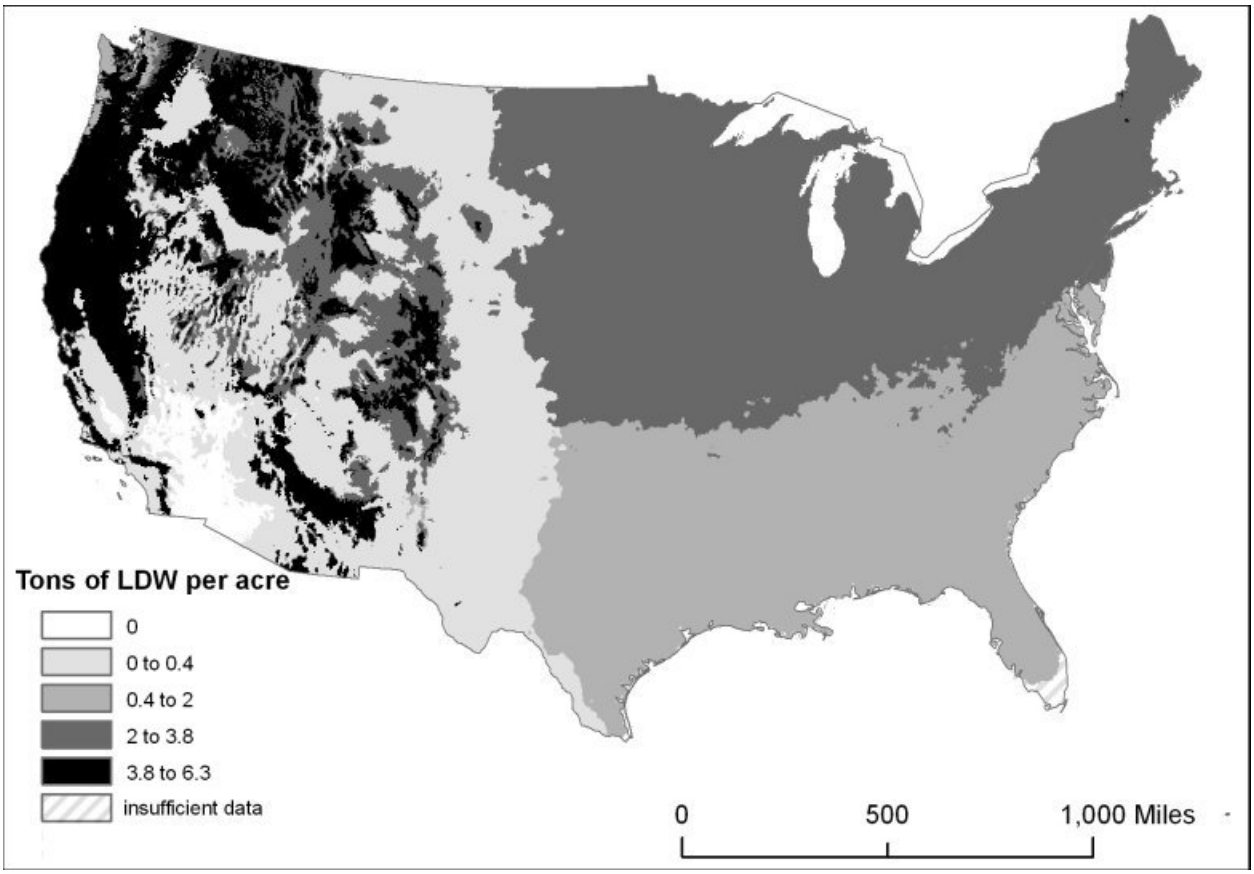

Figure 2 LDW by climatic region, redrawn from Woodall and Liknes (2008)

Table 2 uses the same data source, USFS FIA, and summarizes LDW estimates by U.S. regional carbon stock estimation reporting regions (Woodall et al. 2008).

Table 2 Estimates of LDW by region from Woodall et al. (2008), and LDW as a percentage of total forest carbon (EPA 2010 Table A-216)

Region	Tons of LDW biomass per acre	MT of CO_2eq per acre	LDW as a percentage of total forest carbon
Northeast	3.8	6.3	2.3%
Northern Lake States	4.1	6.8	1.9%
Northern Prairie States	3.3	5.5	2.4%
Pacific Southwest	5.1	8.5	2.9%
Pacific Northwest	10.1	16.9	4.4%
Rocky Mtns. (North)	6.4	10.6	4.6%
Rocky Mtns. (South)	2.4	4.1	2.7%
South Central	1.9	3.2	1.9%
Southeast	2.4	4.1	1.7%

Because regional views of forest carbon include very different forest types, it can also be instructive to view data by forest types. Figure 3 shows FIA data broken into the forest types used throughout Section 4. The differences between Table 2 and Figure 3 reflect the minor forest types included in the regional estimates as well as the distribution of forest types within regions.

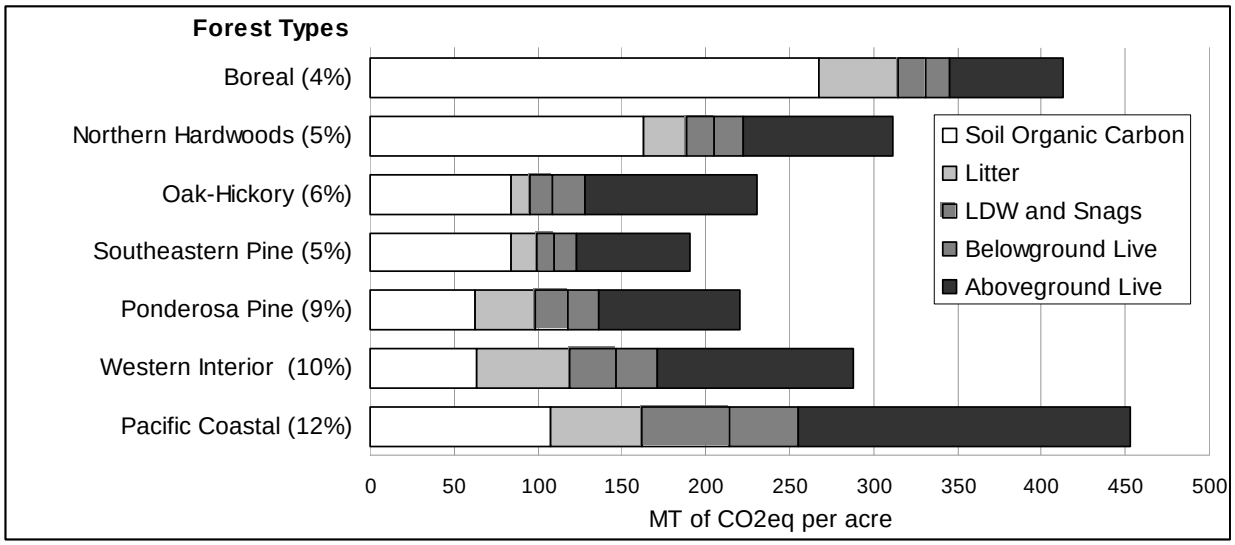

Figure 3 Estimates of carbon stocks by forest type per acre with percentage of LDW and snags in parentheses (EPA 2010 Table A-211)

A significant proportion, from 22% to 65% on average, of the carbon in forests is stored in soils (EPA 2010). When soil carbon is excluded and only aboveground live biomass, belowground live biomass, litter, and dead wood are considered, dead wood makes up a larger percentage of the carbon stored in forest (Table 3).

Table 3 Percentage of Carbon in stored in dead wood (LDW and snags) by forest type (EPA 2010 Table A-211)

Forest Type	Dead Wood as Percentage of Total Forest Carbon	Dead Wood as Percentage of Forest Carbon Excluding Soil Carbon
Boreal	4%	11%
Northern Hardwoods	5%	11%
Oak-Hickory	6%	9%
Southeastern Pine	5%	10%
Ponderosa Pine	9%	12%
Western Interior	10%	13%
Pacific Coastal	12%	15%

New FIA data provides a more detailed view of dead wood and forest carbon storage than has been possible in the past (Chojnacky et al. 2004, Woodall et al. 2008, EPA 2010). However, to appreciate how the snapshot in time represented by the FIA data relates to a specific forest stand requires an understanding of the impact of stand development, natural disturbance, and harvests on the LDW carbon pool. The following section uses local-level research in order to further explain LDW.

Conclusions: National estimates of LDW show that it is a significant pool of carbon, in particular in Pacific Coastal and Western Interior forests. In the U.S., dead wood (both LDW and snags) makes up from 5% to 12% of total forest carbon and quantities of LDW range from about 2 t/ac to 10 t/ac (3.2 to 16.9 MT of CO_2eq/ac). Both the total carbon stored in forests and the distribution between pools changes significantly between forest types.

4. LDW by Forest Type

Separating U.S. forests into useful categories is a difficult task because no one set of divisions works for all purposes. For this review, we have focused on the broadest ecological divisions, generally following Bailey's ecoregions (1995), within which the patterns of, and processes that drive, LDW are similar enough to combine.

4a. Boreal Forests

Most of the boreal forests in the U.S. are found in Alaska, though there is a significant component in the inland areas of Maine as well as on the mountaintops of the northernmost portions of New York, New Hampshire, and Vermont. These ecosystems are usually dominated by white spruce (*Picea glauca*), black spruce (*P. mariana*), balsam or subalpine fir (*Abies balsamea* or *A. lasiocarpa*) (Roi 1967). Boreal forests have cold temperatures that limit decomposition, and soils tend to be relatively coarse and acidic (Barrett 1980). National estimates suggest an average of 3.8 t/ac (6.3 MT of CO_2eq/ac) in LDW for the larger Northeastern region, which includes spruce-fir forests (Woodall et al. 2008). On average, there are about 9.7 t/ac (16 MT of CO_2eq/ac) of dead wood (LDW and snags) in spruce-fir forests in the Northern U.S., which makes up about 3.9% of the carbon stored in these forested ecosystems (EPA 2010 Table A-211).

Boreal forests exhibit the typical U-shaped pattern of LDW over time discussed in Section 3a: a peak early in stand development and a second peak after the stem exclusion phase (Sturtevant et al. 1997, Martin et al. 2005, Brassard and Chen 2006). For example, one study shows a change from 13 t/ac (21 MT of CO_2eq/ac) in a stand less than 20 years old to 4.5 t/ac (7.4 MT of CO_2eq/ac) in the 41- to 60-year age class, to 23 t/ac (38 MT of CO_2eq/ac) in the 61- to 80-year age class, and a return to less than 11 t/ac (19 MT of CO_2eq/ac) in the 101- to 120-year age class (Taylor et al. 2007). Figure 4 shows data for LDW in both t/ac (left Y-axis) and MT of CO_2eq/ac (right Y-axis) over time based on data from Clark et al. (1998), Hély et al. (2000), Fraver et al. (2002), Martin et al. (2005), Brassard and Chen (2006), Taylor et al. (2007), Bond-Lamberty and Gower (2008), Smirnova et al. (2008), Hagemann et al. (2009), and Kranabetter (2009), and bulk density estimates from Krankina et al. (2001) and Woodall and Monleon (2008). Because the data in Figure 4 comes from stands with different site qualities and disturbance histories, the graph does not show the U-shaped pattern of LDW accumulation that a chronosequence from an individual stand would.

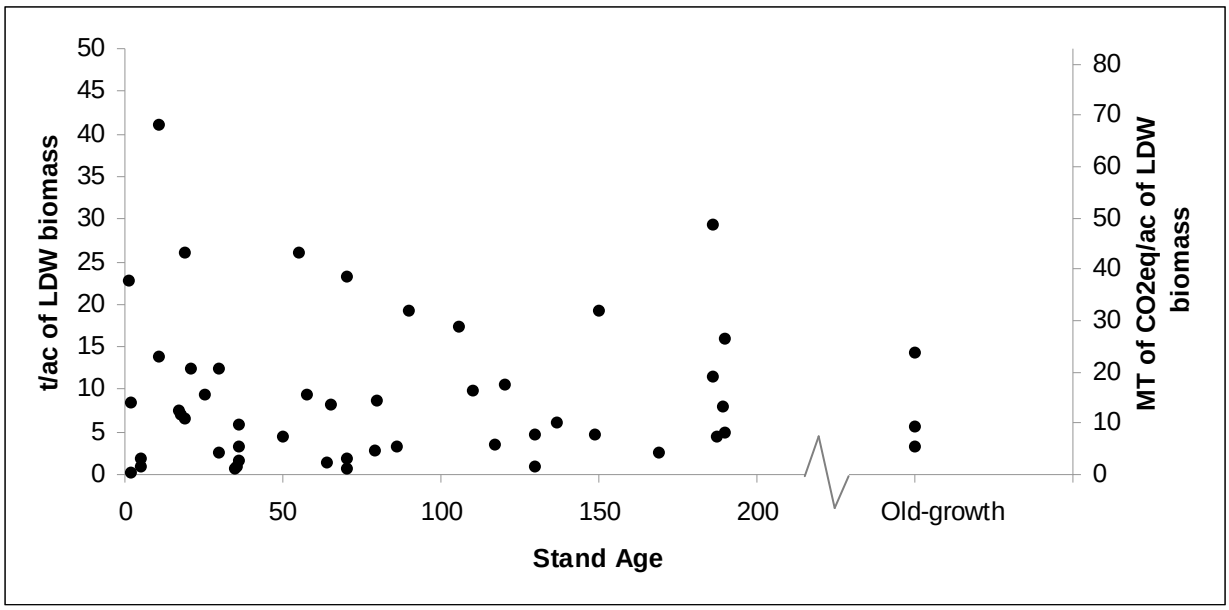

Figure 4 LDW quantities and stand age in boreal forests

Insect outbreaks are a key disturbance process and important producer of LDW in boreal forests. Outbreaks of Eastern spruce budworm occur in cycles of about 35 years in Maine's boreal forests and generate pulses of snags that eventually becomes LDW (Payer and Harrison 2000, Fraver et al. 2002). Fire is another key boreal disturbance process and tends to be more important in Western than Eastern boreal forests. Although fires actively consume LDW as they burn, in the long run they can increase LDW carbon as killed trees eventually fall to the forest floor. For example, in one case LDW increased from 3.1 t/ac pre-fire to 7.6 t/ac (from 5.2 to 13 MT of CO_2eq/ac) 23 years after fire (Slaughter et al. 1998). Other measures of post-fire LDW range from 2.7 t/ac 6 years post fire to 12.8 t/ac 13 years post fire (4.5 to 21 MT of CO_2eq/ac) (Boulanger and Sirois 2006). LDW is likely to peak approximately 20 to 40 years after disturbance, as a result of the collapse of snags (Aakala et al. 2008, Hagemann et al. 2009). An

examination of boreal forests in southeastern Canada suggests that some stands do not have high LDW densities post fire and instead build up LDW as the stand matures (Hély et al. 2000).

Forest management in boreal forests can leave relatively large quantities of LDW immediately after the harvest (Cimon-Morin et al. 2010). For example, a whole-tree clearcut in Maine left 23 t/ac (39 MT of CO_2eq/ac) of LDW after the harvest (Smith Jr. et al. 1986) while a pre-commercial thinning left 15 t/ac (25 MT of CO_2eq/ac) of LDW (Briggs et al. 2000). However, the decay of the initial pulse of LDW generated by the harvest in boreal forests often leaves managed forests with less LDW than unmanaged forests, which have more snags and larger, longer-lasting pieces of LDW (e.g., Briggs et al. 2000, Martin et al. 2005, Brassard and Chen 2008, Weaver et al. 2009). Managed spruce-fir forests in Maine had an average of 3.4 t/ac (5.6 MT of CO_2eq/ac) of LDW (Heath and Chojnacky 2001). A key aspect of the impact of forest management on LDW is the size of LDW pieces. Even-aged harvest methods common in boreal forests are likely to increase the mass of small-diameter, rapidly decaying logging slash (Fraver et al. 2002). Boreal forest management can also reduce the number of snags that generate future LDW (Moroni and Harris 2010). Retention and recruitment of snags, particularly larger-diameter snags, can help ensure that LDW levels are maintained throughout the phases of stand development (Sturtevant et al. 1997, Payer and Harrison 2000, Roberge and Desrochers 2004, Smith et al. 2009a). Uneven-aged or selection silvicultural systems provide more opportunities for snag and LDW retention than even-aged systems (Payer and Harrison 2000, Cimon-Morin et al. 2010).

Conclusions: Dead wood makes up a small percentage (3.9%) of forest carbon in boreal forests. Insect outbreaks and fire tend to generate large quantities of dead wood, first as snags and that as LDW as those snags fall. Similarly, forest management can generate large quantities of LDW, but decay of the initial pulse of harvest LDW often leaves managed boreal forests with less LDW than unmanaged boreal forests. Retention and recruitment of large-diameter snags helps ensure LDW quantities are maintained after the initial harvest pulse of LDW decays.

4b. Northern Hardwoods

Northern hardwood forests are dominated by maple (*Acer* spp.), beech (*Fagus grandifolia)*, and birch (*Betula* spp.), and cover lower elevations and southern portions of Maine, New York, New Hampshire, and Vermont, as well as the northern portion of Pennsylvania. Northern hardwood forests also include conifers, e.g., hemlock (*Tsuga canadensis*) and white pine (*Pinus strobus*), in the mixture (Westveld 1956). A study from New Hampshire provides an example of a Northern hardwood forest following the typical U-shaped pattern of LDW over the history of stand development: a young stand has 38 t/ac (64 MT of CO_2eq/ac) of LDW, a mature stand has 14 t/ac (24 MT of CO_2eq/ac), and an old stand 24 t/ac (40 MT of CO_2eq/ac) (Gore and Patterson 1986). A review of other studies identifies similar temporal patterns and quantities of LDW (see Figure 5, from data described in Roskoski (1977), Tritton (1980), Gore and Patterson (1986), McCarthy and Bailey (1994), McGee et al. (1999), Chokkalingam and White (2001), Fisk et al. (2002), Hura and Crow (2004), Tang et al. (2008), and Bradford et al. (2009). Although this figure combines old-growth stands, research suggests that LDW continues to accumulate as stands age from 200 to 400 years old (Tyrrell and Crow 1994).

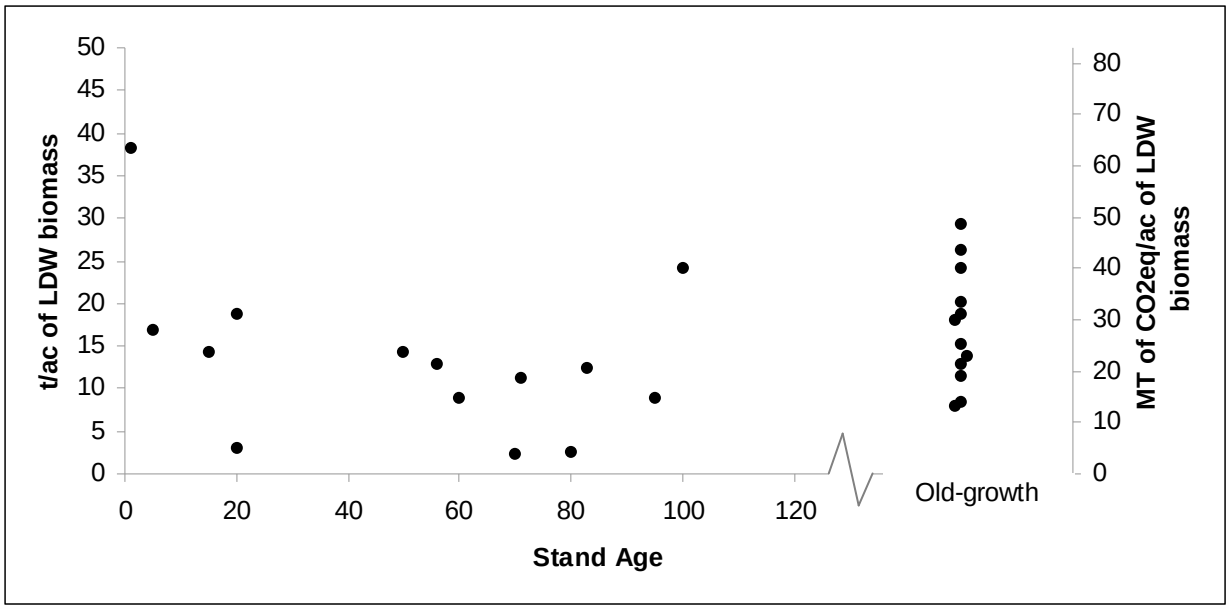

Figure 5 LDW quantities and stand age in Northern hardwood forests

Ice storms and hurricanes are important disturbance processes that generate LDW in Northern hardwood forests. Local biotic and abiotic factors, along with storm intensity, determine the impact of these storms, varying from small scale to stand replacing (White and Pickett 1985, Everham and Brokaw 1996). The amount of LDW added to the system is determined by the specific interactions of storm and forest and cannot be generalized (Webb 1989). Fire plays a small role in LDW accumulation in Northern hardwood forests. However, drought and insects can increase stress, mortality, and therefore LDW. The most obvious examples of this process are non-native insects and diseases such as beech bark disease (*Cryptococcus fagisuga*) or hemlock woolly adelgid (*Adelges tsugae*), both of which have increased mortality and LDW accumulation in affected forests (Orwig and Foster 1998, McGee 2000).

Management generally reduces the amount of LDW in Northern hardwood forests over the long term (Gore and Patterson 1986, Burton et al. 2009, Gronewold et al. 2010), although it often produces a short-term addition to LDW (Liu et al. 2006). For example, an 80-year-old forest from clearcut origin has just 23% of the mass of LDW in a comparable old-growth forest in Michigan (Fisk et al. 2002). However, a stand managed under a selection system (single tree selection on a 20- to 25-year cutting cycle) maintains 83% of the mass of LDW found in a comparable uncut Northern hardwood stand (Gore and Patterson 1986). Treatments designed to encourage the development of old-growth characteristics present the opportunity to maintain high levels of LDW while increasing the size of individual pieces over time (Keeton 2006, Choi et al. 2007). Results in Michigan indicate that leaving at least 90 ft^2/ac of basal area in Northern hardwood forests produces LDW levels 30 years post harvest similar to an unmanaged reference stand (Gronewold et al. 2010). Another study from Michigan documents that old-growth forests have the most LDW, but uneven-aged management maintains more (177%) than even-aged management (Hura and Crow 2004). The reduction of snags is another important effect of harvests. One study in Northern hardwood forests measured a 56% post-harvest reduction in the number of snags (Kenefic and Nyland 2007). Another study measured 7 decaying trees per acre

in old growth, 4/ac in an even-aged stand, and 5/ac in a stand selection system (Goodburn and Lorimer 1998). Given the impact of forest management on snags, researchers have recommended snag retention to augment LDW accumulation (Tubbs et al. 1987). Snags convert to LDW over a period of decades in the Northern hardwoods. A study in New Hampshire found between 18% and 33% of snags still standing for 15 to 20 years after dying (Yamasaki and Leak 2006).

Conclusions: In Northern hardwood forests, dead wood represents an average of 5.2% of forest carbon, but in absolute terms quantities of dead wood are similar to boreal forests (9.7 t/ac or 16 MT of CO_2eq/ac). Unlike boreal forests, old-growth Northern hardwood forests tend to have more LDW than the average for the forest type. The difference between LDW old-growth forests and the average for the forest type may be due to the impact of forest management, which generally reduces LDW in Northern hardwood forests over the long term. Management that encourages old-growth features such as large trees and snags will encourage higher than average levels of LDW in Northern hardwoods.


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4c. Oak-Hickory Forests

Oak-hickory forests occupy a broad swath of the Eastern deciduous forests south of the Northern hardwood forests (Smith et al. 2009b). In this report, oak-hickory forests include both the Appalachian and central hardwoods. This region is dominated by a mix of oak and hickory (*Quercus* spp. and *Carya* spp.) species though a number of other hardwood and pine (*Pinus* spp.) species are also important in the region (Smith and Linnartz 1980). Because of warmer temperatures, processes such as decomposition are generally more rapid than in the Northern hardwoods. In addition, fire plays a larger role. Data from USFS FIA indicate that LDW and snags in oak-hickory forests represent 9.5 t/ac (16 MT of CO_2eq/ac) in the Northeast and Lake States and 5.9 t/ac (9.8 MT of CO_2eq/ac) in the South-central region (EPA 2010).

Idol and colleagues (2001) provide an example of the U-shape of LDW development during the development of an oak-hickory forest: there were 61 t/ac (102 MT of CO_2eq/ac) in a one-year post-harvest stand, 18 t/ac (30 MT of CO_2eq/ac) in a 31-year-old stand, and 26 t/ac (44 MT of CO_2eq/ac) in a 100-year-old stand. Figure 6 includes 10 other studies to provide a more general picture of the range of LDW found in oak-hickory forests as they develop (Macmillan 1988, Onega and Eickmeier 1991, Goebel and Hix 1996, Roovers and Shifley 1997, Spetich et al. 1999, Idol et al. 2001, Muller 2003, Jenkins et al. 2004, Busing 2005, Goebel et al. 2005, Busing et al. 2009).

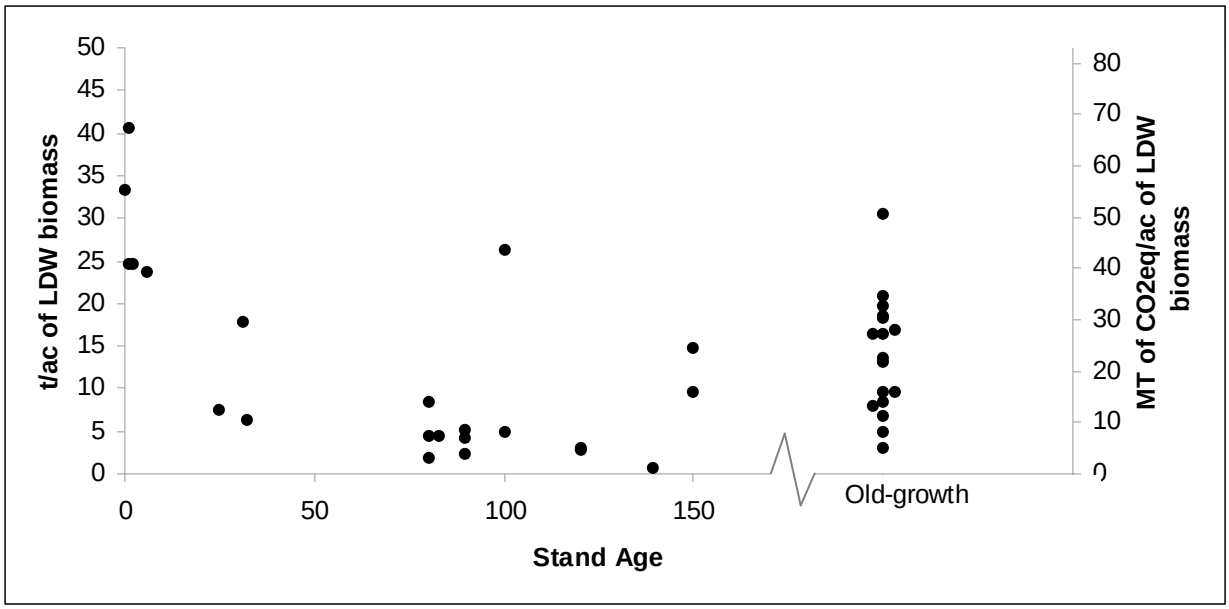

Figure 6 LDW quantities and stand age in oak-hickory forests

Wind storms and ice storms are the primary abiotic disturbances that add to LDW in oak-hickory forests. After one hurricane in North Carolina, the mass of LDW increased nearly eight times (Busing et al. 2009). In the Missouri Ozarks, blowdowns affect approximately 14% of the landscape per century (Rebertus and Meier 2001). An ice storm in Missouri added about 1.2 t/ac (1.9 MT of CO_2eq/ac) of LDW (Rebertus et al. 1997).

LDW does not accumulate in oak-hickory forests over the long term as it does in ecoregions with slower decomposition because of the relatively fast rates of decomposition (Muller and Liu 1991, Graves et al. 2000). Because of this prescribed fire has little effect on LDW (Graves et al. 2000, Greenberg et al. 2006, Loucks et al. 2008). However, consumption of LDW by fire can increase in dry areas, for example, ridge tops (Vose et al. 1999).

Management tends to reduce both LDW and the density of snags that eventually contribute to LDW. For example, a heavy thinning in an Appalachian hardwood stand reduced both LDW and snags from two to four times (Graves et al. 2000). More LDW, including large-diameter pieces, is left on-site after a group selection harvest than after a clearcut in oak-hickory forests (Jenkins et al. 2004).

Conclusions: The more rapid decomposition of oak-hickory in comparison to more Northern forest types means that on average the quantity of dead wood is less (8.3 t/ac or 14 MT of CO_2eq/ac). However, because of lower soil carbon, it makes up a greater proportion of total forest carbon (6.0%). Forest management, particularly clearcutting tends to reduce quantities of LDW. The impact of forest management can be seen in the difference between LDW measurements from old-growth stands in Figure 6 and the average of dead wood for the forest type (8.3 t/ac or 14 MT of CO_2eq/ac).

4d. Southeastern Pine

The pine forests of the Southeast include loblolly (*Pinus taeda*), shortleaf pine (*P. echinata*), slash pine (*P. elliottii*), longleaf (*P. palustri*), and other pines. Before European contact, much of this area was covered by longleaf pine, and low- to moderate-intensity fires were frequent (Van Lear et al. 2005). Much of the area formerly covered by longleaf pine forests and converted to agricultural land has now returned to pine forests (though mostly not longleaf). Forests on former agricultural lands generally have much less LDW than areas that have been continuously forested (Lõhmus and Lõhmus 2005, Bragg and Heitzman 2009). The reduced amount of LDW on former agricultural lands reflects the importance of the pulse of LDW from the disturbance that initiates the new stand. In other words, there is no dead wood on former agricultural lands in the way there is if a new forest regenerates following the death or decline of a previous stand of trees.

Today, many Southeastern pine forests are intensively managed plantations (i.e., planted forests where competing vegetation is suppressed). Plantations have relatively low accumulations of LDW because sites are cleared before planting, rotations are relatively short, and there is a strong financial incentive to capture mortality through harvest rather than leave dead trees to become LDW (Johnston and Crossley 2002, Carnus et al. 2006). For the same reasons, Southeastern pine plantations have low numbers of snags; for example, 72% of a comparable natural forest stands in a South Carolina study (Moorman et al. 1999). International surveys indicate that about 1 t/ac (1.6 MT of CO_2eq/ac) of LDW is common for plantations; this LDW tends to be made up of small pieces (Tobin et al. 2007, Brin et al. 2008). Similarly, pine plantations in Georgia and South Carolina measure 1 t/ac (1.7 MT of CO_2eq/ac) and 1.6 t/ac (2.6 MT of CO_2eq/ac) respectively, while natural pine forests in those states have about four and 2.5 times that much LDW respectively (McMinn and Hardt 1996). A survey across the Southeast shows that loblolly plantations do not reach 1 t/ac of LDW (1.6 MT of CO_2eq/ac) until about 30 to 35 years of age (Radtke et al. 2004). Too few data are available on the quantity of LDW in Southeastern pine forests to provide a figure for this forest type.

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Disturbance agents such as Southern pine beetle (*Dendroctonus frontalis*) and wind storms can create large quantities of LDW in Southeastern pine forests. Loblolly is most susceptible to bark beetle attack, slash is more resistant, and longleaf is the most resistant. However, in areas of intensive management downed trees are salvage logged, i.e., removed because of damage or mortality caused by insects, disease, or any other factor except for competition (Loeb 1999). Fire is a natural part of the disturbance regime in Southeastern pine forests and continues to play an important role, often as prescribed fire in plantations. LDW increases after prescribed fire, beginning about two years after the burn, when snags began falling (Greenberg 2003). In another

study, prescribed fire and mechanical thinning both increased LDW about 42%, while a combination of mechanical thinning and burning reduced LDW by 30% (Kilpatrick et al. 2010).

Conclusions: Southeastern pine forests have the lowest average quantity of dead wood of the forest types discussed in this paper (6.2 t/ac or 10 MT of CO_2eq/ac). Since they also have the lowest total forest carbon, the percentage of carbon in dead wood (5.5%) is similar to oak-hickory or Northern hardwoods forests. The prevalence of plantations, which tend to have very low levels of LDW, likely reduces the average quantity of dead wood in these forests. Site preparation and the short rotations common to plantation management tend to reduce LDW. In Southeastern pine forests under uneven-aged management, retention of large snags and large pieces of LDW encourages buildup of LDW, even with frequent fires.

4e. Ponderosa Pine

The range of ponderosa pine (*Pinus ponderosa*) in the U.S. extends from Washington State to southern New Mexico. Though ponderosa pine is often found in combination with other species, in many places it is the dominant species in ecosystems adapted to relatively frequent, low-severity fires. For example, prior to Euro-American settlement, surface fires burned through Southwestern ponderosa pine forests every 4 to 12 years (Covington and Moore 1994). However, natural fire regimes have been disrupted across millions of acres of ponderosa pine forests since the late 1800s as a result of fire suppression, logging, and livestock grazing (Cooper 1960, Lynch et al. 2000). Past logging that focused on the removal of large trees continues to affect forests because it has created a lack of large snags and large pieces of LDW.

In general, LDW levels are lower in ponderosa pine forests than in the other Western forest types discussed in this paper, and the U-shaped pattern of LDW accumulation is less pronounced. The combination of snags and LDW in ponderosa pine forests of the Rocky Mountains is about 7.3 t/ac (12 MT of CO_2eq/ac) (EPA 2010). The relationship between stand age and LDW accumulation is made more complex by the role of fire and the prevalence of multi-aged stands (Brown and See 1981). A study using a large number of USFS inventory plots was unable to detect a relationship between age and LDW in the Northern Rocky Mountains (Brown and See 1981). However, a study focused on a chronosequence of ponderosa pine stands in Colorado did identify the typical U-shaped pattern of LDW accumulation: LDW amounts peaked about 19 years after fire, decreased to a minimum about 81 years post fire, and then increased in old stands (Hall et al. 2006). Even low-intensity fires can remove a large portion of LDW in ponderosa pine forests, e.g., in one case 99% of large, rotten wood (Covington and Sackett 1984). In the absence of fire, rates of LDW decomposition tend to be low in ponderosa pine forests because of low precipitation (Erickson et al. 1985). Figure 7 shows the general pattern of LDW accumulation over time in ponderosa pine forests (Sackett 1979, Covington and Sackett 1984, Sackett and Haase 1996, Youngblood et al. 2004, Passovoy and Fulé 2006, Finkral and Evans 2008, Busse et al. 2009, Chatterjee et al. 2009, Keyser et al. 2009).

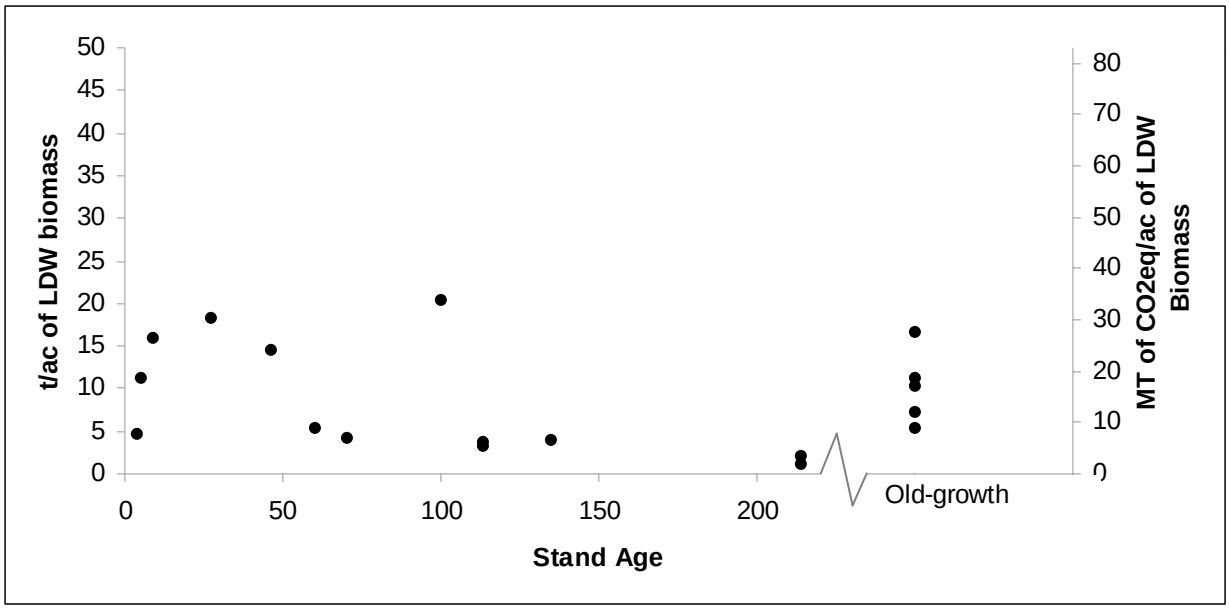

Figure 7 LDW quantities and stand age in ponderosa pine forests

Though ponderosa pine forests are generally adapted to low-severity fires, higher-severity fires may occur in patches, or even over larger areas because of uncharacteristically high tree densities. High-severity fires kill more trees, tend to create more snags, and eventually result in more LDW. After the Jasper Fire of 2000, high-severity patches had 24% of the LDW of unburned patches while low severity patches had 21%, and LDW increased in the high-severity patches more rapidly in the years after the fire (Keyser et al. 2008). Approximately 50% of snags produced by a stand-replacing fire will fall within the first 7 to 12 years (Everett et al. 1999, Keyser et al. 2008, Keyser et al. 2009). Salvage logging after a fire can reduce the amount of LDW by 36% in ponderosa pine forests (Keyser et al. 2009). Insect attacks, particularly those by bark beetles, are another cause of mortality and a source of LDW (Negrón et al. 2009).

Harvesting in ponderosa pine forests is often accompanied by prescribed fire or conducted in preparation for the return of a low-severity fire regime. Thinning with removal of cut trees has little effect on the quantity of LDW in ponderosa pine forests (Youngblood et al. 2006, Finkral and Evans 2008, Busse et al. 2009, Sorensen 2010). A stand managed with an uneven-aged system has about 69% of the LDW in a comparable, more intensively managed stand (Chatterjee et al. 2009). More intensively managed stands often have less LDW. However, data from Chatterjee and colleagues (2009) underscore the point that uneven-aged management is not a guarantee of increased LDW. In this case, a firewood removal included in the uneven-aged management likely reduced LDW (Chatterjee et al. 2009). In some cases, prescribed fire increases the levels of LDW (Busse et al. 2009), while other research shows prescribed fires reduce the LDW between 44% and 69% (Covington and Sackett 1984, Sackett and Haase 1996, Youngblood et al. 2006). Fire consumes significantly more of the decayed LDW than sound pieces (Uzoh and Skinner 2009).

The USFS recommends retention of at least 3 snags per acre in ponderosa pine forests in the Southwest (Reynolds et al. 1992); however, actual snag densities are often lower (Ganey and

Vojta 2005). The average large snag (>18" in diameter) density in ponderosa pine forest in northern Arizona is 0.4 per acre in managed forests and 2.3 in unmanaged forests (Ganey and Vojta 2005). Similarly, the current amount of LDW in Southwestern ponderosa pine forests is less than USFS recommendations (USFS 1999, Ganey and Vojta 2010). Recommended management targets for LDW include 5.4 to 13 t/ac (8.9 to 22 MT of CO_2eq/ac)(Graham et al. 1994) and 5 to 10 t/ac (8.3 to 17 MT of CO_2eq/ac) for the warm dry Western forest types (Brown et al. 2003).

Conclusions: Ponderosa pine forests tend to have less total forest carbon than other forest types, but a higher percentage (8.9%) of that carbon stored in dead wood as well as a comparatively large absolute amount of carbon in dead wood (12 t/ac or 20 MT of CO_2eq/ac). A central issue with LDW in ponderosa pine is fire. Historically, forests dominated by ponderosa pine tended to have frequent fires, but in many areas fire no longer plays its natural role. Frequent fire is likely to consume small pieces of LDW (those of less than 1" in diameter), but the larger the piece of LDW the more likely some of it will survive. Past harvesting that removed a significant proportion of the large trees has created a lack of LDW in many ponderosa pine forests. Government guidelines encourage increased retention of large snags and retention of between 5 and 13 t/ac (8.3 and 22 MT of CO_2eq/ac) of LDW.

4f. Western Interior Coniferous Forests

Other Western coniferous forests are also adapted to fire, but many have longer intervals between fires than ponderosa pine forests. This review combines a range of forest types in the interior West that share moderate to infrequent fire regimes, such as lodgepole pine forests and mixed conifer forests. In general, as the time between fires increases, fire severity—and hence tree mortality—increases. Differences in fire return interval can drive LDW dynamics (Stephens et al. 2007). A study in Oregon showed twice as much LDW in forests with an infrequent, stand-replacing fire regime (300 years) as in landscapes having a moderately frequent fire regime (125 years) (Wright et al. 1999). Table 4 shows the range of LDW amounts from inventories of 10 Western interior national forests (Brown and See 1981).

Table 4 LDW on 10 Western interior national forests (from Brown and See 1981)

Forest Type	t/ac of LDW biomass	MT of CO_2eq/ac of LDW biomass
Ponderosa pine	3.9	1.8
Douglas-fir	9.6	4.4
Lodgepole pine	13.9	6.3
Spruce-subalpine fir	20.2	9.2

Even in fire-adapted Western forests, stand age can influence LDW accumulation. For example, old-growth Western larch (*Larix occidentalis*) and Douglas-fir (*Pseudostuga menziesii*) stands in northwestern Montana had three times the carbon stored in LDW as young stands (Bisbing et al. 2010). However, as mentioned above, a study of USFS inventory plots was unable to detect a relationship between age and LDW in the northern Rocky Mountains (Brown and See 1981), and a different study of 64 plots ranging from 35 to 150 years post fire showed no correlation between age and LDW accumulation (Dordel et al. 2008). The accumulation of LDW in old-

growth forests of the interior West is due, in part, to the slow decay rates in cool, moisture-limited environments. LDW increases at higher elevations and cooler temperatures because of this slow decomposition (Erickson et al. 1985, Kueppers et al. 2004). In these cold, dry environments, logs can take up to 600 years to disappear completely (Brown et al. 1998, Kueppers et al. 2004).

Figure 8 includes data from a range of forest types from the interior Western U.S. that all have moderate to infrequent fire regimes, though most data points are from lodgepole pine forests (Busse 1994, DeLong and Kessler 2000, DeLong et al. 2003, Kueppers et al. 2004, Litton et al. 2004, Chatterjee et al. 2009, Bisbing et al. 2010).

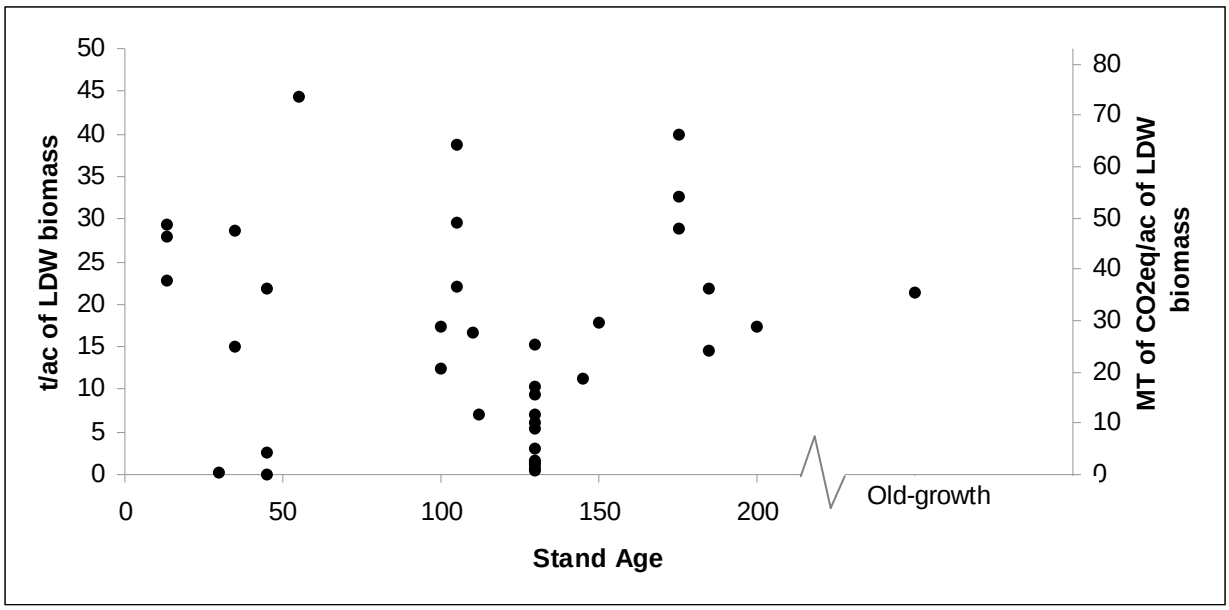

Figure 8 LDW quantities in Western interior coniferous forests

The most important mortality agents in Western coniferous forests include mountain pine beetle (*Dendroctonus ponderosae*), Western spruce budworm (*Choristoneura occidentalis*), root diseases (e.g., *Armillaria* spp., *Phellinus weirri*, or *Heterobasidion annosum*), dwarf mistletoe (*Arceuthobium* spp.), and fire (Steed and Wagner 1999). Mountain pine beetle outbreaks can add up to four times pre-outbreak quantities of LDW to lodgepole forests (Busse 1994, Klutsch et al. 2009), while Western spruce budworm can double the amount of LDW (Hummel and Agee 2003). Fifteen years after a mountain pine beetle outbreak, stands had 50% more LDW than comparable unaffected stands; but 45 years after an outbreak, LDW levels had returned to normal (Dordel et al. 2008). Salvage logging after insect outbreaks generally increases LDW in the short term because snags and branches are converted to LDW, but in the long term can reduce LDW levels. In one example, salvage logging after a mountain pine beetle outbreak reduced LDW to below pre-outbreak levels within 20 years (Lewis 2009). Trees recently killed by disturbance or even slash piles can become breeding sites for bark beetles such as the pine engraver (*Ips pini*) that then spread to healthy trees.

The moderate- to high-severity fires common in these Western interior forests can consume a significant portion of LDW (Boerner et al. 2008). In Yellowstone National Park, fire consumed

about 8% of the LDW and converted another 8% to charcoal, effectively moving 8% of the carbon from the LDW pool to the soil pool (Tinker and Knight 2000). Fuel consumption rates are higher in the Sierra Nevada mixed conifer forests, where they range from 45% for spring burns to 88% for fall burns (Kauffman and Martin 1989, Knapp et al. 2005). Fire tends to reduce the size, length, and volume of LDW (Knapp et al. 2005). Because even stand-replacing fires in lodgepole pine forests leave most of the pre-fire stem biomass on-site, they eventually generate large quantities of LDW in the absence of salvage harvesting (Wei et al. 1997, Tinker and Knight 2000). In contrast, clearcut regeneration harvests in lodgepole pine remove more of the stem biomass and generate less LDW. In one study, whole-tree harvesting left 18% of stem biomass as LDW, while stem-only harvesting left 24% (Wei et al. 1997). The LDW left after harvest also tends to be made up of smaller pieces, which decay relatively quickly (Wei et al. 1997).

Thinning treatments combined with prescribed fire have been shown to increase snag density and eventually result in LDW buildup (Boerner et al. 2008, Harrod et al. 2009). In Sierran mixed-conifer forests, both thinning and prescribed fire have been shown to reduce LDW quantities, and burning reduces piece size (Knapp et al. 2005, Stephens and Moghaddas 2005, Innes et al. 2006). These differing results show that treatment specifics result in different impacts on LDW carbon.

Conclusions: As in the case of ponderosa pine, the natural moderate- to high-severity fire regimes of many Western interior forests have been altered. Reducing the role of fire in fire-adapted ecosystems has important consequences for carbon in LDW. Current LDW levels may be higher than historic levels because of fire suppression, though forest management often reduces LDW more than fire alone. Fires also create charcoal, which adds carbon to the soil carbon pool. Management, particularly salvage logging or whole-tree harvesting, tends to reduce LDW over the long term. On average, Western interior forests have 17 t/ac (28 MT of CO_2eq/ac) of dead wood, which is approximately 9.9% of their total carbon.

4g. Pacific Coastal Forests

The forests of the Pacific coast are very productive, contain the highest levels of biomass, and hold the most LDW of all U.S. forests (Busing and Fujimori 2005, Woodall et al. 2008, EPA 2010). Coastal forests include redwood (*Sequoia sempervirens*), Douglas-fir, hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*), all of which are long-lived species. Stand-replacing disturbances are infrequent, resulting in long time periods for LDW accumulation in unmanaged forests. However, warm and wet conditions increase rates of decomposition in comparison to dry ponderosa pine forests or cool and dry Western interior forests (Erickson et al. 1985). Even with these relatively high rates of decomposition, LDW can remain in the Pacific coastal forests for 1,000 years, perhaps because of the large size of the LDW in this region (Feller 2003). Pacific coastal forests tend to follow the U-shaped pattern of LDW accumulation over time (Feller 2003). A classic study of nearly 200 Douglas-fir stands identified 19 t/ac (32 MT of CO_2eq/ac) of LDW in stands less than 80 years old, 8.9 t/ac (15 MT of CO_2eq/ac) in stands 80 to 120 years old, and 29 t/ac (49 MT of CO_2eq/ac) in stands 400 to 500 years old (Spies et al. 1988). Figure 9 shows the high level of LDW in Pacific coastal forests and generally reflects the U-pattern of LDW accumulation over time (Grier 1978, Spies et al. 1988, Means et

al. 1992, Acker et al. 2000, Janisch and Harmon 2002, Brunner and Kimmins 2003, Feller 2003, Harmon et al. 2004, Busing and Fujimori 2005, Janisch et al. 2005, Ares et al. 2007).

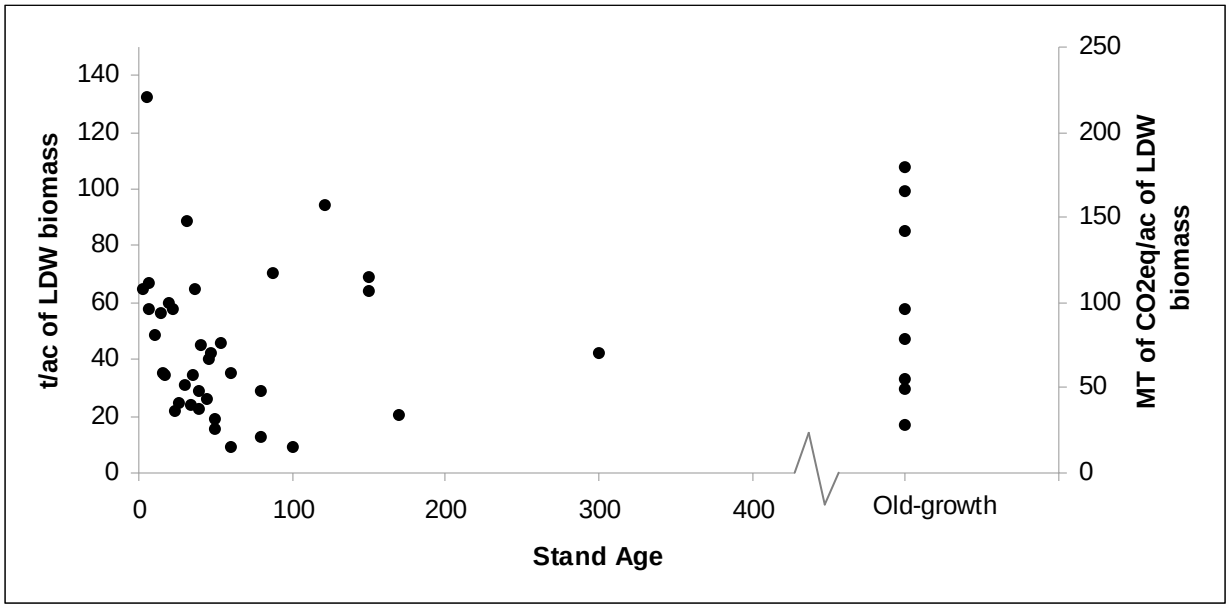

Figure 9 LDW quantities in Pacific coastal forests

Wind storms in these coastal forests are a periodic disturbance which can more than double the amount of LDW (Brunner and Kimmins 2003). Insect outbreaks, such as Western spruce budworm, can double LDW in Pacific coastal forests (Hummel and Agee 2003). Fires are infrequent, stand re-initiating events in Pacific coastal forests, with a return interval on the order of 250 to 500 years (with shorter intervals in drier sites) (Busing and Fujimori 2005). Few data exist on the LDW impact of fire in Pacific coastal forests.

Managed forests have less LDW, and individual pieces of LDW tend to be smaller than in unmanaged Pacific coastal forests (Spies and Cline 1988, Stevenson et al. 2006). Large logs can make up the majority of LDW in Pacific coastal forests. For example, in one study old-growth logs made up 77% of the mass of LDW nearly 50 years after the initiation of a new stand (Ares et al. 2007). In coastal Oregon, most early-successional forests are the product of timber harvesting and lack legacy dead trees (Ohmann et al. 2007). However, in one example harvesting generated significant quantities of LDW in the short term (7.5 t/ac; 12 MT of CO_2eq/ac) (Harrington and Schoenholtz 2010). Two rotations of intensive management can reduce LDW by 90% compared to old-growth forests (Rose et al. 2001). In an experimental harvest in Washington state, bole-only harvests increased LDW 36% while whole-tree harvests reduced LDW 50% (Ares et al. 2007). A simulation study suggests that harvests with 20% retention of live trees could retain up to 70% more dead wood than a clearcut harvest (Harmon et al. 2009). Removal of logging slash after harvest was shown to reduce the amount of LDW by 39% in mature coastal Douglas-fir plantations (Harrington and Schoenholtz 2010).

Snags are the other key source for LDW in Pacific coastal forests. Snag longevity is determined in large part by species and size. In second-growth coastal forests, Douglas-fir snags last about

16 years, while hemlock snags last 11 years (Parish et al. 2010). Single-tree or group selection can be used to preserve trees and snags in order to minimize LDW reductions after harvests (Stevenson et al. 2006).

Conclusions: Of the forest types in this review, Pacific coastal forests have the most total forest carbon, the most dead wood (31 t/ac; 52 MT of CO_2eq/ac), as well as the highest percentage of forest carbon in dead wood (12%). Large old-growth logs in Pacific coastal forests contain a great deal of carbon and can last for centuries. Because they often lack these large log legacies from previous stands, managed forests have less LDW than unmanaged Pacific coastal forests. Therefore, preserving large logs and snags in managed forests helps maintain LDW. Bole-only harvests and retention of 20% of live trees can increase LDW in Pacific coastal forests.

5. Conclusions

5a. Importance of LDW Carbon Storage


Jeff Smith

LDW is an important pool of carbon throughout the U.S., ranging from about 2 t/ac to 10 t/ac of biomass (3.2 to 16.9 MT of CO_2eq/ac). Based on regional averages, LDW makes up from 1.7% to 4.6% of total forest carbon, though in individual stands LDW can make up a much larger percentage of total forest carbon (e.g., Chatterjee et al. 2009, Harmon et al. 2004, Martin et al. 2005, Taylor et al. 2007). If soil carbon is excluded, dead wood (LDW and snags) makes up between 9% and 15% of forest carbon (Table 3). Both the quantity of LDW and the percentage of total forest carbon it represents vary notably between regions and forest types, as illustrated by Figure 3 and Table 2. These differing levels of LDW are driven by the disturbance regimes and stand development processes specific to each forest type. Because of this variability, LDW retention requirements should be as ecologically specific as possible, at least to the level of the forest types described in Section 4.

In addition to storing carbon, LDW plays other important roles in the ecosystem, such as wildlife habitat, erosion protection, water storage, and nutrient cycling, as discussed in Section 1a. In many forested ecosystems, increased LDW benefits carbon storage and these other ecological values at the same time. In other words, LDW maintained for wildlife habitat or nutrient retention also increases carbon stocks. However, there are situations where increasing LDW for carbon storage is at odds with other ecological goals. The clearest examples of potential negative ecological impacts of increased LDW retention are insect outbreaks and high-severity fire. Some insects, particularly engraver beetles (*Ips* spp.), breed in slash and fresh LDW and then attack live trees; still, risks involved with retaining existing or large pieces of LDW are relatively small. LDW can also pose a fire threat, so human health and safety concerns can justify maintaining

low levels of LDW near developed areas. Even in areas where humans are not at risk from fire, the ecological impact of uncharacteristic high-severity fires may justify maintaining low levels of LDW. Where high severity fires are not part of the historic fire regime, they can have negative impacts such as conversion to non-forest cover. High-severity fires also move large amounts of carbon from forest pools to the atmosphere, so retaining less LDW where it contributes to the threat of high severity fire may store more carbon over the long term. Striking the balance between LDW retention for ecological values, including carbon, and fire threat management requires site-specific evaluation.

A comparison of the importance of carbon storage relative to the other values of LDW is difficult, but it could determine how guidance for LDW retention is derived. If carbon is paramount, then LDW retention should be based on its carbon content, whereas if other ecological values are more important then they should determine retention levels. The comparison between carbon storage and other ecological values of LDW is hampered by the lack of a common metric with which to compare them. One argument against basing LDW retention guidance on the carbon it stores is the uniqueness of the other ecological roles LDW plays. Other forest structures (such as live trees) could sequester the carbon lost from LDW, but nothing can replace the habitat, hydrologic function, regeneration, or nutrient cycling role that LDW plays.

5b. Management Effects on LDW Carbon

The management effects on LDW carbon are complex and must be considered within the context of natural cycles of LDW change, which often follow the U-shaped pattern as forests age. Even without management, LDW carbon may decline as a forest moves from the stand initiation phase into the stem exclusion phase. Clearly, management activities that remove LDW at stand initiation will reduce LDW carbon for decades, until stands develop sufficiently so that competition and disturbances begin to generate new LDW. Similarly, forest management decisions that remove small pieces of LDW will have a more transient effect on the LDW carbon pool than decisions that remove large pieces of LDW, because large pieces take longer to decay and are only available in stands with mature or old trees. This review also emphasizes the link between snags and the LDW they become. Forest management activities that change snag densities will eventually have an impact on LDW carbon.

Disturbances add another element of complexity to the relationship between management and LDW carbon. The impact of a salvage harvest on LDW carbon may not be noticeable immediately after the harvest, because of logging residues. However, salvage harvesting tends to reduce LDW carbon as the stand develops because of the removal of snags, which provide a long-term source of dead wood to the LDW pool. Suppressing fire in frequent-fire ecosystems may cause an initial increase in LDW because of reduced consumption by fire of LDW, later trigger a decrease because of reduced mortality, and eventually cause a large increase in LDW by facilitating high-severity fire (and potentially stand conversion).

In planning for the maintenance of LDW carbon, managers need to consider the common disturbances for each forest type. Many disturbances, such as wind storms or insect outbreaks, add to LDW carbon. Where disturbances add to LDW accumulation, salvage plans should take into account the possibility that other sources of LDW may be reduced for decades after the

disturbance. LDW wood retention also needs to be balanced with the forest health risks posed by insect populations that build up in dead trees, as well as the potential fire threat from increased surface fuel. In areas where disturbances, notably fire, may reduce the LDW carbon pool, management strategies should focus on maintaining large pieces of LDW that are unlikely to be completely consumed and will remain on-site for decades.

The general precepts above and specific examples cited throughout Section 4 demonstrate that selection systems offer the opportunity to maintain snags and trees that will add to LDW over time. For example, studies show that uneven-aged management can maintain significantly more LDW than even-aged systems—and moreover, approach the levels of unmanaged forests—in Northern hardwoods (Hura and Crow 2004, Gronewold et al. 2010), boreal forests (Payer and Harrison 2000, Cimon-Morin et al. 2010), oak-hickory forests (Jenkins et al. 2004), and Pacific coastal forests (Stevenson et al. 2006). Of course, any silvicultural system appropriate to the forest type can be adapted to promote maintenance and development of the LDW carbon pool. Individual tree reserves, group reserves, or a combination of both can be integrated into silvicultural systems to ensure large snags and LDW are part of the stand structure. Obviously, protection of individual large pieces of LDW or snags helps maintain LDW carbon as well.

5c. Projects to Increase Carbon Stored in Forests

The Reserve's Forest Project Protocol recognizes three types of projects that increase carbon storage on forestland: reforestation, improved forest management, and avoided conversion. Reforestation projects would increase carbon stored in LDW as trees grow and die. Avoided conversion projects would protect existing LDW carbon from release. The more complex issue is the effect of improved forest management projects on LDW carbon. Each project will have slightly different impacts on LDW depending on site conditions, forest type, the stage of stand development, and forest management activities. However, some generalizations are possible based on the eligible management activities for improved forest management projects, which may include

- increasing the overall age of the forest by increasing rotation ages
- increasing the forest productivity by thinning diseased and suppressed trees
- managing competing brush and short-lived forest species
- increasing stocking of trees on understocked areas

Increasing rotation ages is likely to have two complementary effects on LDW carbon. First, increasing stand age will allow more time for LDW buildup in some forest types, such as Pacific coastal, Northern hardwoods, or ponderosa pine forests. Second, it is likely to increase the piece size, longevity, and hence carbon storage in LDW over time. However, in forest types where insect outbreaks are driven by tree age (e.g., some boreal forest types), increasing overall age may have adverse effects on forest carbon. The impact of thinning diseased and suppressed trees on LDW carbon is difficult to determine because it depends on the extent to which thinning reduces the number of potential snags, and hence LDW. If thinning of low-vigor trees allows more rapid development of larger dominant trees, and some of those trees are allowed to become snags or LDW, it could increase LDW carbon. However, if thinning of low-vigor trees removes all snags and potential LDW, it could drastically reduce LDW carbon. The efficient removal of low vigor trees is one reason plantations have low levels of LDW, as discussed in section 4d. Managing competing brush and short-lived species is likely to increase LDW by speeding up

stand development. Similarly, increasing the stocking of trees in understocked areas is likely to increase LDW, both because more live trees are available to become LDW and because increased competition will result in more snags and LDW. Some improved forest management projects focus on increasing stocking above regional averages and thereby increase carbon storage. Higher-than-average stocking levels are likely to increase competition, tree mortality, and hence LDW. However, stocking levels higher than regional averages may slow individual tree growth and hence the development of large pieces of LDW.

Another question is whether incentives to maintain carbon in live trees will drive landowners to remove LDW instead. A switch from live trees to LDW is unlikely, because LDW is low-quality wood with a low economic value. Moreover, FPP accounting currently includes snags, and these standing dead trees provide a supply of LDW. The economic impacts of greater LDW retention are discussed below in section 5d.

In general, improved forest management projects are unlikely to have a negative impact on long-term LDW carbon storage for two main reasons: First, FPP projects usually employ uneven-aged silvicultural practices, which, as section 5b details, are more likely to maintain LDW carbon. Second, the main eligible management activities are, on balance, likely to increase LDW carbon. Of course the specific impacts of a FPP project will depend on which management activities are implemented.

5d. The Economics of LDW and Leakage


Christopher Riely

One possible outcome of increased LDW retention is a shift of harvesting activities to other forestlands (i.e., leakage). A full analysis of the leakage effect of increased LDW retention requires in-depth market assessments, evaluations of landowner preferences, and economic modeling (Trømborg and Solberg 2010). However, even without detailed analysis some trends are clear. For example, in general LDW has a low economic value. Most current LDW has some decay and is not suitable for timber. The trees that become snags (and then LDW) tend to be suppressed or damaged and hence have low economic value. In some areas (particularly the Southeast), markets for wood pulp exist and increased LDW retention could cause a direct shift of harvesting activities to other forestlands. In most areas, one of the few markets for material that is (or will soon become) LDW is bioenergy, but this material is of so little value even for bioenergy that its removal must often be subsidized (Evans and Finkral 2009). Harvest and transport of low-value forest biomass is expensive relative to the market value for the material (Ralevic et al. 2010). As bioenergy prices rise, the demand for wood from the bioenergy sector will likely be met by a combination of trees that would have traditionally been used for timber production and increased collection of material that would become LDW (Stennes et al.

2010). In some cases, waste wood from urban sources (e.g., construction debris) is a less costly feedstock for bioenergy than wood from forests (Perlack et al. 2005).

Often the economic cost of increased LDW retention is related to an increase in operational costs or opportunity costs. Retaining LDW and snags on-site can increase forest management costs because dead wood adds complexity and safety concerns to forest operations. For example, planting is easier and cheaper where LDW is not an impediment. Retention of snags and suppressed trees that will become LDW takes up space that could be occupied by higher value timber trees, so LDW retention could be an opportunity cost. Because increased LDW retention may increase the cost of forest management, there may be an incentive to increase timber production in other areas to offset this cost. Another potential leakage effect of increased LDW retention is related to fire and fuel reduction. Millions of dollars are spent to reduce the amount of LDW and to otherwise reduce the fire threat in fire-adapted forests across the Western U.S. (Snider et al. 2006). Increased retention of LDW in some stands may lead to increased fire threat, or the perception of increased fire threat, and hence more fuel reduction thinning and LDW removal in nearby stands.

In summary, the risk of leakage caused by increased LDW retention requires a full analysis beyond the scope of this report. Greater LDW retention could drive more harvesting in other areas by increasing forest management operational costs. Similarly, the increased fire threat (or perception of fire threat) of high levels of LDW in fire-adapted forest could spur fuel reduction thinnings. However, the risk of leakage from increased LDW is likely relatively low where no pulp market exists because of the low value of trees that become LDW.

Chapter 2: Measuring Lying Dead Wood

6. Methods Overview and Statistical Background

In this section, we provide an overview of field methods for estimating the abundance of LDW, paying particular attention to carbon and biomass. As we discuss elsewhere, the primary practical means of estimating carbon or mass of LDW is to estimate cubic volume (ft^3/ac or m^3/ha) by decay class, taxonomic group, and/or size class and then to apply appropriate conversion factors, so much of the discussion will revolve around obtaining accurate volume estimates.

What does it mean to obtain an accurate estimate? The ideal estimate of LDW carbon would exactly match the number we would obtain if we tallied every piece of LDW within an area of interest and applied perfect measurement techniques to each piece. In practice, it is not reasonable to tally every piece of LDW unless the area of interest is very small. Moreover, LDW measurements are even more challenging than those for standing trees because of breakage and decay, which make LDW "logs" even more irregular and heterogeneous than their live counterparts.

In the design of a successful LDW inventory protocol, it is critical to distinguish between *sampling error* (the component of inaccuracy that arises because only a portion of the population of logs in an area has been tallied) and *nonsampling errors* (which arise from inaccurate measurements and, perhaps more importantly, the inevitable errors made by field personnel confronting the operational challenges of sampling and measurement). Both sources of error are important. While much research in forest biometrics concentrates on the former, Deming (1960) argues that the latter can be more important for management-oriented problems. Westfall and Woodall (2007) found that measurement repeatability for the FIA downed wood protocol failed to meet desired standards for 15 out of 27 LDW variables, implying significant nonsampling errors. Although those errors had minimal effect on plot-level estimates in their study, their presence underscores the importance of nonsampling error in developing field protocols for LDW inventory. It is also important to include error-checking procedures in the design (Woodall et al. 2008); taper rates (i.e., rates of change in diameter as one moves along a piece of LDW) and length to diameter relationships (e.g., joint distributions of length and large-end diameter) may be helpful in this regard (Woodall and Westfall 2008).

Accuracy is most often described in terms of two main components: bias and variance. Both can be explained in terms of *statistical expectation*. If x is a random variable—one that depends on, say, the outcome of the random selection of a plot location in an inventory—then the statistical expectation of x, denoted as $E[x]$, is the average of x over all possible plot locations (weighted, if necessary, by the probability of selecting specific plot locations if plots are not located uniformly at random). Now, suppose that C is the true carbon density of LDW (MT of CO_2eq/ac) in a tract of interest, and $\hat{C}$ is the estimate we obtain from a particular inventory. The *bias* of that particular inventory protocol is the average difference (averaging over all the inventories that *could* have been obtained using that protocol) between the results of a single inventory and the true value:

$$\text{bias} = \mathrm{E}\left[\hat{C} - C\right] \qquad [1]$$

If bias is zero, that inventory is said to be unbiased. Note that unbiasedness is not a property of a particular inventory result, only of the protocol that generated it. One might get lucky and obtain an estimate close to the true value even if the protocol is biased, or conversely one might get an estimate far from the true value even if the protocol is unbiased. All unbiasedness guarantees is that possible overestimates (including those large enough to cause management errors) are balanced against the possibility of underestimates; there is no systematic distortion of results. The statistical property that is most commonly used to describes the tendency of an estimate to fall close to its long-run average is its *variance:*

$$\text{variance} = \mathrm{E}\left[\left(\hat{C} - \mathrm{E}\left[\hat{C}\right]\right)^2\right] \qquad [2]$$

When the variance is that obtained by considering the variability of estimates calculated from individual observations (such as sample points or plots), we call its square root the *standard deviation*; when the variance is that of the final estimates from an overall effort (typically including many points or plots), we call the square root of the variance the *standard error.* Although variance, standard deviation, and standard error are often used to describe the familiar bell-shaped normal or Gaussian distribution, the concepts apply to nearly all other probability distributions. We shall frequently refer to the variance of estimates, but nothing in this paper assumes normality (or any other particular distribution).

A statistic that describes the overall accuracy of an estimate, including both its bias and variance, is the mean squared error or MSE:

$$\text{mean squared error} = \mathrm{E}\left[\left(\hat{C} - C\right)^2\right] \qquad [3]$$

which can also be calculated as

$$\text{mean squared error} = \text{bias}^2 + \text{variance} \qquad [4]$$

One can immediately see from this equation that there may be a tradeoff between bias and variance for overall accuracy. For example, if Protocol A is unbiased but has a large variance, while Protocol B trades a small amount of bias for a dramatic reduction in variance, Protocol B may be the more desirable even though it is slightly biased. However, variance often arises principally from sampling error, and it can be reduced by increasing the sample size. So the performance of an unbiased protocol can often be improved by increasing the sample size (or employing other variance reduction tactics, such as stratification), while the performance of a biased protocol is eventually limited by its bias no matter how large the sample size. Whether it is practical to increase the sample size often depends on the cost of the methods employed, but (especially in the case of LDW inventory) the sample size may be fixed by other considerations. For example, we would anticipate that the sample size (and spatial arrangement) for LDW will typically be driven by the live overstory sample size, which has considerably more financial value and typically also contains more carbon. A key criterion for LDW methods, then, is whether they can deliver a reasonable bias/variance tradeoff for an acceptable cost when integrated with an overall forest inventory strategy whose sampling approach and sample size are fixed.

7. Common Sampling and Measurement Challenges

Several features of LDW present challenges for efficient inventory. Some of these challenges are unique to LDW, while others are common to multiple forest carbon pools but deserve special mention in the LDW context. Six issues of general concern are

- LDW as a rare, spatially clumped population with strong spatial pattern
- The need to allocate sample points or lines appropriately within a tract
- Boundary slopover issues
- Visibility
- Measurement accuracy challenges, especially for cross-sectional area and volume
- Consistency in assignment of decay classes

To avoid unnecessary repetition in the description and discussion of individual LDW sampling methods below, we will describe some of these issues here with attention to how they impact most or all methods, and then deal with exceptions and special cases as they arise.

7a. Spatial Arrangement of LDW

Unless an area of interest has been the subject of a recent catastrophic disturbance, such as a stand-replacing windthrow, wildfire, or landslide, LDW will typically be a much smaller carbon pool than the standing overstory (see, for example, the review of regional patterns in Section 4). Although the sheer number of LDW pieces per acre may be large, especially if minimum length and/or diameter criteria are small, the number that contribute substantially to the carbon pool can be quite low. Moreover, because the processes that drive tree mortality (such as natural disturbance, self-thinning, and timber harvest) tend to be clumped at the stand and substand scales, LDW tends to have a patchy distribution. The sparse and patchy distribution of LDW makes it unreasonable to expect that inventory methods designed with the live overstory in mind will produce LDW assessments with comparable accuracy. For example, one should not expect that 0.2-acre plots, or modified prism sweeps with a BAF 10 prism, conducted at the same points where (or the same number of points which) the live overstory is inventoried to provide confidence intervals on the final estimates of LDW that are broadly similar in percentage terms.


Brian Milakovsky

Because many LDW pieces are (at least to a first approximation) linear, LDW also has orientation, a property we do not associate with the live overstory. Many of the processes that generate LDW (such as windthrow) tend to create LDW populations with a shared orientation. This is especially true of mechanized logging, and of site preparation techniques such as windrowing. Furthermore, the tendency of LDW to roll in steep terrain can tend to align LDW pieces even if the initial fall direction is random. Therefore, we believe it is important to be suspicious of inventory approaches that assume uniform random orientation of LDW pieces. That assumption is unlikely to hold for real LDW populations and it can introduce appreciable bias.

Moreover, for some (though not all) methods, whether or not LDW pieces in the population tend to have a shared orientation can have a substantial impact on variance.

7b. Allocation of Sample Points or Lines within the Tract

LDW may be a minor carbon pool, but that does not mean estimates of LDW carbon should be based on samples that are fundamentally flawed. Most of the methods for LDW inventory reviewed below center on sample points (in the same way that circular plots or prism sweeps for measuring the overstory do). For these methods, it is important to avoid arbitrary, subjective, or convenience samples. Rather, sample points should be selected according to a known probability design. Most often, this will be a systematic or simple random sample of points within inventory strata (which would typically be defined in terms of overstory species, size, and density in an ordinary forest inventory). For line-based methods, the options expand to include selection probabilities that are either uniform or proportional to line length. A full treatment of these issues is well outside the scope of this review, but violation of these basic principles can render LDW estimates fundamentally indefensible (and also potentially legally inadmissible; see, e.g., Daubert v. Merrell Dow Pharmaceuticals, 509 U.S. 579 (1993)). Readers seeking a full treatment should consult standard inventory and sampling texts.

7c. Boundary Slopover

Boundary slopover occurs whenever objects in a population (in our case, pieces of LDW) lie close enough to the boundary of a tract that they could be tallied from outside the tract. If sample points are only located inside the tract, and if field procedures are not modified or appropriate adjustments made to the usual estimating equations, then estimates of the amount of material inside the tract will be biased downward. This problem arises with all sampling methods, including fixed-area plots, and has been of concern in forestry at least since the work of Finney and Palca (1949). Unfortunately, the causes of this bias and its cures have often been poorly understood. The common approaches of either rejecting sample points that fall near the boundary or "pulling back" sample points until they are no longer near the boundary (cf. Lee et al. 1997) both exacerbate rather than reduce the bias (Williams et al. 1996, Gregoire and Scott 2003). As Gregoire (1982) highlights, the cause of bias is objects near the boundary, not sample points near the boundary.

Boundary slopover is of special concern for LDW inventory because many sampling methods employ relatively large inclusion zones, particularly for large LDW. This tends to aggravate slopover bias, so proper correction for slopover may be more important for LDW than it is for the live overstory. Fortunately, for most of the methods discussed here standard approaches to slopover bias elimination or reduction are directly applicable and are simple to perform in the field. These standard methods include the following:

- The mirage method (Schmid 1969, Gregoire 1982). This method is only applicable when boundaries are straight lines. It requires additional care when inclusion zones are not circular (Ducey et al. 2001), which is the case for many useful LDW methods. It also requires establishing sample points outside the tract boundaries.

- The walkthrough method (Ducey et al. 2004). This method is applicable to arbitrarily complex boundaries and oddly-shaped inclusion zones. It is very fast to implement in the field and does not typically require work or travel outside the tract boundary.
- The toss-back method originally proposed by Haga and Maezawa (1959), or the related area-free method developed by Flewelling and Iles (2004). Although originally developed within the context of prism sampling, both approaches generalize readily to LDW inventory (Ståhl et al. 2001). However, both require sampling outside the tract boundary, which may be disadvantageous in some applications.

Special options or issues for slopover correction with specific methods will be discussed on a case-by-case basis below. Valentine et al. (2006) review options for slopover correction when cluster plots are used. An applications-oriented review of boundary slopover issues can be found in the text by Iles (2003, chapter 14).

7d. Visibility

Nondetection bias—the failure to tally objects that should have been included in a sample, typically because the objects were not seen—is a familiar problem in inventories of the live and dead overstory (cf. Wensel et al. 1980, Wiant et al. 1984, Ducey et al. 2002). However, the problem is especially aggravated in LDW inventory. Because LDW is (by definition) lying on or near the ground, it can be completely obscured by tall understory vegetation. LDW in advanced stages of decay can be covered completely by moss, litter, or low herbaceous vegetation. Finally, pieces of LDW that are fragmented into short lengths may escape notice in the cluttered visual field of the forest understory. Researchers developing and testing new LDW methods have commented extensively on this challenge. For example, Bebber and Thomas (2003) state that in a field trial of their method, finding LDW obscured by vegetation and litter presented some difficulties. Affleck (2009) points out that in sloping terrain, or in the presence of a heavy understory, simple search strategies (such as those employed by line intersect sampling) may be more effective than complex visual searches. Nondetection due to poor visibility is an important source of nonsampling error in LDW inventories and it should be considered in advance in inventory design.

7e. Measurement of Cross-Sectional Area

Recall from calculus that the volume of any solid, including LDW, can be written as

$$V = \int_L A(l)\,\mathrm{d}l \qquad [5]$$

where V is cubic volume, L is the length of the solid along a straight-line axis, and $A(l)$ is the cross-sectional area measured perpendicular to that axis, at a distance l along the axis. Equivalently, one may write

$$V = \overline{A}L \qquad [6]$$

where $\overline{A}$ is the mean cross-sectional area taken along the axis. It should come as no surprise that all known methods for LDW inventory require a measurement of cross-sectional area at one or more positions on some, if not all, tallied pieces in order to obtain a volume estimate as a prerequisite to estimating carbon content.

Unfortunately, the assumption that stem cross-sections are circular—never quite accurate for live standing trees, though usually close enough that the difference is negligible—can be quite inappropriate for LDW. Breakage, collapse, and fragmentation can result in cross-sections that are far from circular. This is especially true at piece endpoints, where many volume formulae assume measurements will be taken but where breakage may result in the loss of a considerable (but irregular) portion of the cross-section. For intact pieces, Fraver et al. (2007) document a reduction in the average ratio of the vertical to horizontal axes to as little as 0.38 as LDW decays (the ratio would be 1.0 if pieces were circular). Fraver et al. (2007) also point out that in their study the most decayed and flattened pieces were not sampled, so the ratios reported should not be regarded as extreme.


Christopher Riely

As Fraver et al. (2007) discuss, most LDW studies measure piece diameter horizontally (i.e., parallel to the forest floor), most often with calipers, and then assume circularity for calculating cross-sectional area, but this procedure can introduce a bias that depends on decay class. Measuring the diameter vertically with calipers is probably not practical for many pieces, except in research studies (though Harmon and Sexton (1996) write, "The maximum and minimum diameters are easily measured"). Harmon and Sexton (1996) recommend the use of an elliptical approximation when trees have flattened due to decay. Kenning (2007) reports success using a sharpened probe, employed in a fashion similar to a bark gauge, to find the average depth of advanced-decay LDW by resistance (the average depth, multiplied by width, gives an estimate of cross-sectional area that is more accurate than assuming an ellipse). Very few authors have addressed volume or carbon losses due to hollowness or internal decay. In practical work, it may be necessary either to develop a local relationship for the species mixture and decay class system, or to employ subsampling to correct for non-circular cross-sections.

7f. Measurement of Volume

Many (though by no means all) LDW inventory methods require estimates of individual piece volumes in order to obtain an estimate of LDW volume per acre. This presents special challenges for LDW above and beyond those that arise for live trees or merchantable logs (cf. Fraver et al. 2007). Having one or more accurate measurements of cross-sectional area does not guarantee an accurate estimate of the volume of individual LDW pieces; these measurements must be combined in such a way as to produce an accurate estimate of the average cross-sectional area of the piece (see Equation [6]).

Foresters have long employed volume formulae derived from classical quadrature. *Quadrature* is the mathematical technique of evaluating an integral (such as that of Equation [5]) without an exact formula. Quadrature rules used in forestry include the familiar Huber's, Smalian's, and

Newton's formulae (cf. Husch et al. 2003) as well as less-common formulae such as Hossfeld's (Ducey and Williams *in review*). Of the common formulae, Newton's typically shows the least bias, Huber's shows a slight downward bias, and Smalian's gives a substantial upward bias when applied to live trees or sections thereof; Fraver et al. (2007) found similar results in a study of LDW. Unfortunately, Newton's equation is the most demanding, requiring not only log length but also three cross-sectional area measurements (one at each end, and one at the midpoint of the log). Although Harmon and Sexton (1996) state that taking measurements at both ends and the midpoint "allows one to avoid assuming any particular form such as a cone or neiloid," there are indeed specific assumptions about the range of piece shapes associated with all quadrature formulae, and even Newton's cannot be assumed to be completely unbiased. No published study has compared Hossfeld's equation to other approaches for estimating LDW volume, but given its mathematical similarity to centroid sampling (discussed below) it might be an attractive alternative. The study by Fraver et al. (2007) also explored the average-of-ends formula, the conical frustum formula, and a novel conic-paraboloid formula. Their conic-paraboloid requires no midpoint measurement, showed high accuracy and should be considered for use when LDW methods require volume estimates for individual pieces and economy of measurement is important.

It is possible, of course, to avoid volume formulae entirely and rely on a sampling approach to estimate volumes of individual LDW pieces. Techniques that would be applicable include importance sampling (Furnival et al. 1986, Gregoire et al. 1987, Van Deusen and Lynch 1987, Wiant et al. 1992), control-variate sampling (Gregoire et al. 1987), and crude Monte Carlo (Valentine et al. 1992). The centroid sampling approach (Wood et al. 1990) is conceptually related to importance sampling, and trades a small amount of bias for a reduction in variance by using a fixed sampling point that must be calculated once the cross-sectional area has been measured at the two ends of a piece. Wiant et al. (1996) compared centroid, importance, and control-variate sampling for intact boles and found the centroid approach to be most precise, despite a small bias. The paracone model (Forslund 1982) can be similarly motivated (Lynch et al. 1994). We know of no published study specifically comparing these techniques for LDW, but their potential applicability is clear.

Some LDW methods have "built in" options for obtaining piece volumes by sampling methods, including line intersect sampling, critical point relascope sampling, critical length sampling, perpendicular distance sampling, and line intersect distance sampling. We will deal with volume estimation in each of these methods as they arise. In principle, these methods obviate the need to measure cross-sectional area at other predetermined points (such as the ends). However, information on, e.g., large-end diameter distribution is often desired by resource managers (Woodall et al. 2008, Bate et al. 2009). Woodall et al. (2008) suggest it may be possible to estimate unmeasured large- and small-end diameters using predictive models. Furthermore, in several of these methods it is unnecessary to measure log length to estimate volume per acre. Not only is log length a relatively costly measurement (from a time perspective), it is also associated with a great deal of measurement error (Woodall and Westfall 2007, Woodall et al. 2008).

7g. Assigning Decay Classes

In addition to volume, decay class is commonly used to determine the carbon content of individual LDW pieces (or portions thereof). For example, the USFS FIA program uses a 5-class decay rating system, with Class I being least decayed and Class V most decayed (cf. Woodall and Williams 2005, p. 12). The FIA system follows the general framework of Maser et al. (1979) and Sollins (1982), on which much subsequent work has been built. In situations where entire pieces are measured for volume, it is also common to assign a "representative" decay class to the entire piece (cf. Pyle and Brown 1999). This typically involves an element of subjectivity even if the criteria for different decay classes are objective. The impact of this potential source of bias on large-scale LDW carbon estimates has not been well-quantified for LDW. Fasth et al. (2010) examined the repeatability of decay class assignment for fine fuels and note these difficulties as well. As noted above, however, several methods do not require the assignment of an overall decay class, but can provide valid estimates when the decay class is estimated only at a unique position on the log associated with volume estimation. These include line intersect sampling, critical point relascope sampling, critical length sampling, perpendicular distance sampling, and line intersect distance sampling.

8. Summary of Methods


David Affleck

When Harmon and Sexton (1996) published their rough guidelines for measuring LDW in the Long Term Ecological Research network, there were only two primary methods available for inventory: fixed area plots and line intersect sampling. The past 14 years have seen a dramatic increase in the development of new techniques as interest in LDW has risen, and the shortcomings of the older techniques have become apparent. Here, we will review 7 major categories of methods, recognizing that some include special cases that are of interest in their own right. For example, critical length sampling (Ståhl et al. 2010) is included in the section on prism sweep methods, while critical point relascope sampling (Gove et al. 2005) is included in the section on point relascope sampling. We do not include guided transect sampling or adaptive cluster sampling, as these approaches have not been extensively tested for LDW inventory (and, in the case of adaptive cluster sampling, when tested have been found to be less efficient than other methods (Pesonen et al. 2009)). A review of those two approaches, along with some others that are reviewed here, can be found in Ståhl et al. (2001). Any of the methods discussed here can be used to evaluate change in LDW over time (for example, to compare initial baseline LDW carbon with actual evolution of LDW carbon following project implementation), though all of the methods would benefit in their efficiency from the establishment of permanent sample points or lines. Valentine et al. (2008) review change estimation procedures for LDW with specific attention to perpendicular distance sampling (PDS). A very brief summary of the methods reviewed here, along with their principal strengths and weaknesses, is given in Table 5.

Table 5 Summary of Sampling Methods

Method	*Strengths*	*Weaknesses*	***Key References***
Fixed Area Plots	Familiar. Useful for small-scale ecological studies.	Time consuming and inefficient. High risk of non-detection.	Ståhl et al. 2001
Line Intersect Sampling (LIS)	Simple search path. Low probability of non-detection. Easy boundary correction (in some cases).	Large sampling effort required. Restrictive assumptions.	Kaiser 1983, Ducey 2001
Transect Relascope Sampling (TRS)	Reduces sampling effort relative to LIS. Can reduce assumptions needed in LIS (in special cases).	Choice of gauge angle is important. Little field testing to date.	Ståhl 1997, 1998
Point Relascope Sampling (PRS)	Relatively well tested among novel methods. Very efficient under some circumstances.	Choice of gauge angle is important. Most efficient with crews of 2 or 3. Non-detection may be problematic.	Gove et al. 2001
Prism Sweep Method	Prisms familiar to foresters. Most efficient when LDW is in relatively intact pieces.	Not widely tested. Bias in volume estimates from Huber's formula.	Bebber and Thomas 2003
Perpendicular Distance Sampling (PDS)	Potentially fast when used by experienced cruisers. Outperforms LIS in some field tests.	Efficiency depends on rapid visual search. Inefficient if cruisers cannot estimate diameter and distance visually. Potential non-detection.	Williams and Gove 2003, Williams et al. 2005a, b
Line Intersect Distance Sampling (LIDS)	Combines low non-detection error of LIS with potential statistical efficiency of PDS.	Very little field testing to date.	Affleck 2009a

8a. Fixed Area Plots

Basic Description

In principle, sampling LDW using fixed area plots is simple and familiar: circles, squares, or rectangles of known area are laid out at a series of sample points, and the LDW on the plot is tallied and measured. If the area of the plots is *a*, then each tallied piece contributes 1/*a* pieces per acre to the estimate associated with that plot. Harmon and Sexton (1996) emphasize square and rectangular plots, but as with standing tree inventory the choice of plot shape is largely a matter of field efficiency and individual preference rather than theory. Indeed, some researchers use long strips for LDW inventory (cf. Bate et al. 2002, Lutes 2002) and other than the usual accounting for possibly unequal-length strips the approach is conceptually similar to fixed-plot inventory (Ståhl et al. 2001).

However, as Ståhl et al. (2001) discuss, the simplicity ends there. There are at least two main approaches to determining what LDW is "in" a plot. In one set of approaches, a piece of LDW is entirely in if some uniquely identifiable point on the piece is in. For example, Vanderwel et al. (2008) used the midpoint of LDW pieces to determine their inclusion on permanent sample plots. In this situation, obtaining estimates of pieces per acre and volume per acre is nearly identical to the procedures for doing so with standing trees. However, some LDW may physically lie on the plot but may not be included in the sample. Conversely, other workers have specifically included only the LDW elements that fall on the plot, excluding those portions of LDW pieces that fall across the plot border. This approach seems to be anticipated by Harmon and Sexton (1996), and would certainly be easiest with square or rectangular plots because pieces would be cut off by straight lines. Ståhl et al. (2001) point out that this latter approach entails tedious measurements on individual pieces to find the portion of the piece to include, and that it also precludes unbiased estimation of number of pieces per acre. Nonetheless, it is a theoretically valid approach that could be useful for certain purposes.

Plot size is a key operational concern, and a wide range of plot sizes have been reported in the literature. For example, LDW is inventoried using fixed-area plots under the ForestBIOTA program under the European Union Regulation (EC) No 2152/2003 (Forest Focus). This program inventories all fallen trees on 50x50 meter plots, and fallen pieces of trees on four 7-meter-radius subplots within each plot (Travaglini et al. 2007). This level of sampling effort is probably far beyond what most operational inventories for LDW carbon can sustain.

Required Measurements

Depending on the protocol, fixed area plot sampling requires measurements to characterize the entire volume and overall decay class of every LDW piece that has a predefined unique point (such as the pith at the large end, or at the midpoint) falling in the plot, or the same data but only for those portions of the LDW pieces that lie in the plot. Typically, these measurements would include the length, one or more cross-sectional areas (depending on the volume equation used), and an estimated overall decay class. Forked LDW can be problematic, as volume must be determined for the entire piece, though the multistage approach recommended by Gove et al. (2002) in the point relascope sampling context could also be employed with fixed plots. Borderline pieces should be checked carefully. Standard techniques for correcting boundary slopover apply to fixed-area plots (though see Ducey et al. (2001) for a cautionary note about the

mirage method if rectangular plots are used, or if plot corners, rather than plot centers, are randomly or systematically located in the tract).

Special Advantages

Perhaps the greatest advantage of fixed area plots for LDW is their familiarity. If live trees are being inventoried on fixed plots, it may be possible to track individual LDW pieces "from cradle to grave" and thus provide an accounting of the components of carbon change in addition to net sequestration. This may be one reason why of 33 countries identified by Woodall et al. (2009) that survey LDW as part of their national inventories, 63% use fixed area plots. However, Woodall et al. (2009) note with some regret that protocols provided were often insufficiently detailed to determine what field procedures were used to determine whether LDW was "in" and whether the estimating equations being used were appropriate to the design.

Researchers occasionally treat inventories from fixed area plot samples as "real" numbers for comparison with other methods (cf. Lutes 2002, Osborne et al. undated), but this reflects a fundamental misunderstanding of sampling. Samples from fixed-area plots are still samples, and they are subject to both sampling and nonsampling errors in the same way that all other samples are. A complete census of the population on a reference area (cf. Bate et al. 2002) provides a benchmark that excludes sampling error but may still be subject to nonsampling errors (including inaccurate measures of cross-sectional area and/or volume, as well as nondetection errors). Indeed, some researchers have pointed out the difficulty in avoiding nondetection on fixed-area plots, as the entire plot must be searched for small and/or cryptic LDW (e.g., Jordan et al. 2004, Kenning 2007).

Operational Challenges and Sources of Bias

As noted above, nondetection is a primary concern with fixed area plots. A more fundamental challenge for carbon assessment, however, is that fixed area plots include LDW with probability proportional to piece frequency. Thus, a great deal of measurement effort may be expended searching for, and measuring, pieces that contribute relatively little to overall carbon estimates, while large LDW is sampled so infrequently that the variance of the estimates is large (cf. Ståhl et al. 2001). The result can be a combination of crew-numbing tedium, time-consuming search, and high variance that leads to aggravated nonsampling error as well as unacceptable statistical efficiency.

Zander Evans

8b. Line Intersect Sampling

Basic Description

Line intersect sampling (or the nearly indistinguishable line intercept sampling) has been used widely for a range of ecological sampling tasks, dating at least to Canfield (1941). Line intersect sampling (hereafter LIS) was originally adapted to LDW inventory by Warren

and Olsen (1964). Other early papers on LIS and related methods for LDW surveys include van Wagner (1968), Bailey (1970), and Brown (1974). The authoritative work on statistical aspects of LIS is Kaiser (1983). However, many readers find Kaiser (1983) impenetrable. The treatment by de Vries (1979, 1986) provides additional theory with a similar lack of clarity. As Ståhl et al. (2001) write, "it [LIS] is somewhat difficult to describe in a simple way from a theoretical point of view." A simplified treatment for practitioners has been presented by Ducey (2001).

In a typical inventory case, LIS involves laying out a line (or cluster of lines, for example an X- or Y-shaped cluster comprised of two or three lines respectively) centered on a sample point. (It is also possible to employ long transects that cross an entire tract, akin to the strips in a strip cruise.) All the LDW pieces that cross the sample line are tallied; all others are ignored. If volume per acre is the only parameter to be estimated, then the only measurement needed on individual pieces is their cross-sectional area at the intersection with the sample line and perhaps the slope of the piece. LIS tallies individual LDW pieces with probability proportional to their length (which is a key contributor to piece volume), so (ignoring time considerations, and focusing on the relationship between variance and number of logs measured) it is more efficient for estimating LDW volume than fixed-area plots. For example, Sikkink and Keane (2008) found that line intersect sampling was the most efficient of five techniques (including fixed plots and three photoload techniques) for estimating biomass of woody fuels, but that at least 1.5 km of line were required for reliable estimates. Although Sikkink and Keane's (2008) analysis has been criticized for taking inadequate account of sampling time in the evaluation of efficiency (Wright et al. 2010), that criticism does not appear to impact their judgment of the relative merits of fixed area plots and line intercept sampling.

Although LIS has been used in ecology for nearly 7 decades, the method remains confusing to both researchers and practitioners, as evidenced by the number of inaccurate or even blatantly wrong statements about LIS that appear in the literature (Gregoire and Valentine 2003). For example, Lutes (2002) states that LIS requires two assumptions: that pieces are oriented randomly, and that they are situated randomly on the forest floor. The first assumption is only required if sample lines are not oriented randomly (and, depending on measurements taken, may not be required even then), and the second never applies.

Required Measurements

The required measurements and associated calculations for LIS depend somewhat on the approach taken and the assumptions one is willing to make about LDW. A foremost consideration is whether or not one considers logs to be randomly oriented, whether the sample lines are randomly oriented, and if neither is true whether or not one is willing to take additional measurements to satisfy the formal assumptions of the method. The most commonly presented estimating equations (such as those in Shiver and Borders (1996), and those presented in the practitioner guide by Ducey (2001)) assume that the *intersections* between LDW pieces and LIS sample lines occur at angles drawn uniformly at random. This occurs either if LDW pieces are at random angles, or if the LIS sample lines themselves are laid out on random bearings. Many authors, following de Vries (1979), employ a model-based assumption that LDW pieces are randomly oriented. However, this is unlikely to be true, as outlined in the introductory material in this chapter. Moreover, failure to demonstrate non-random orientation of LDW by failing to reject the null hypothesis in a test does not establish that LDW is, in fact, randomly oriented. As

Ducey (2001) points out, random orientation of LIS lines is not difficult to achieve but it is rarely practiced. More commonly, LIS is conducted using clusters of sample lines with different orientations at each sample point, in the hope that this will ameliorate any directional bias (cf. Woldendorp et al. 2004). For example, the USFS FIA protocol uses Y-shaped clusters that take advantage of the orientation and position of the fixed-area subplots for standing trees (Woodall et al. 2008). Waddell (2002), Woodall and Williams (2005), and Woodall et al. (2008) provide a concise review of this design, along with its associated estimators and procedures for converting downed wood volume to carbon. Other published examples include equilateral triangles (Delisle et al. 1988) and the L-shaped layout used by the British Columbia Ministry of Forests (Marshall et al. 2000). Gregoire and Valentine (2003) suggest that alternative estimators should be used when clusters of sample lines are employed. They also suggest that the statistical advantages of such clusters may not have been established objectively, and that further research may be needed in that area. As an example, Woldendorp et al. (2004) found no increase in precision when samples of equal length were laid out in clusters to capture orientation variability.

An alternative approach is to treat both LDW orientation and sample line orientation as fixed. In that case, it is necessary to measure the "width" of each tallied LDW piece (i.e., its length projected perpendicular to the sample line). Equivalently, the angle of intersection of each piece can be recorded along with its length, and the "width" can be calculated trigonometrically. Ståhl et al. (2001) detail this approach when the sample lines are simple (i.e., not laid out in clusters), noting that it is almost certainly less efficient than using randomly oriented lines. Gregoire and Valentine (2003) describe estimators under these assumptions for line clusters. A practical concern is that when LDW pieces are nearly parallel to the sample line, their "width" is very small and this can lead to individual pieces representing astonishing volumes per acre in the estimating equations. (An LDW piece strictly parallel to the line should not, in theory, ever be tallied but if it were its contribution to volume would be infinite. For LDW that is nearly parallel, the imprecision of angular measurement can swamp other sources of variability in the entire inventory.)

Let us assume for the moment that LIS sample lines are laid out at random, or that a cluster has been used and the residual bias is believed to be within acceptable levels. Then the only additional measurements needed on individual LDW pieces in order to estimate volume are the cross-sectional area at the intersection point and the slope of the piece if it is not horizontal. Although Harmon and Sexton (1996), following van Wagner (1968) and Brown (1974), suggest that piece slope is unimportant for large logs, Monleon (2009) demonstrates that failure to account for slope results in an overestimate of volume per acre of up to 8%.

There is lingering debate in the literature about the tradeoff between using volume estimated from the cross-section at the intersection point, and that which would be obtained by measuring log length and the cross-sections at predetermined points (such as the ends, followed by volume estimation using Smalian's formula). Monleon (2009) argues for using the crossing point diameter and, given both the potential for bias and the increase in measurement effort required for Smalian's formula (at a minimum log length and one more cross-section), that recommendation seems reasonable.

Special Advantages
A particular advantage of LIS is its exceedingly simple search path. Pieces to be tallied must cross the sample line, so this should result in very low levels of nondetection error (cf. Jordan et al. 2004, Affleck 2009a). Because of visibility issues, LIS may be the only practical option in some forested conditions (e.g., Amazonian rainforests) (Keller et al. 2004, Palace et al. 2007).

The mirage or reflection method for correcting boundary slopover bias is especially easy to implement for LIS, and is fully described by Gregoire and Monkevich (1994). Bate et al. (2008) suggest a "bounce back" method that appears to be a variant of the mirage method (though they cite no papers on slopover correction), but their proposed technique is clearly less efficient in the field than that of Gregoire and Monkevich (1994). The use of clusters of LIS transects at each sample point can greatly complicate slopover correction; Affleck et al. (2005) review the challenges and provide solutions for certain cases.

Operational Challenges and Sources of Bias
Although nondetection should be minor with LIS, that does not mean other sources of nonsampling error are unimportant. Ringvall and Ståhl (1999a) examined operator errors in line intersect sampling. In their study, they found a noticeable underestimate caused largely by cruisers straying from the correct sampling line and away from logs. Such errors seem most likely when long sampling transects are used, and provide a nonsampling motive for using larger numbers of short sample lines rather than fewer but longer lines to inventory LDW. Conversely, Woldendorp et al. (2004) follow Harmon and Sexton (1996) in arguing for relatively long sample lines (100m, or approximately 5 chains, at each sample point). We shall return to this issue below.

Bate et al. (2009) report bias in estimates of frequency, percent cover, volume, and weight when using intersect diameters rather than large-end diameters in LIS. However, their study reflects a fundamental confusion about the role of intersect diameters and large-end diameters in the classification and measurement of logs. As highlighted above, Monleon (2009) reports that volume estimation using the crossing point diameter is preferable to the use of Smalian's formula with the end diameters, introducing very little variance in exchange for the elimination of a key source of bias.

The greatest challenge in using LIS for LDW inventory is the required sampling effort. The simulation studies by Pickford and Hazard (1978) and Hazard and Pickford (1986) suggest that an aggregate line length of 1 to 4 km would be needed for reliable estimates in any inventory stratum, and these general conclusions seem to be borne out in field studies in a range of forest conditions (cf. Jordan et al. 2004, Kenning 2007). Ducey (2001) recommends a rule of thumb that to achieve confidence limits for LDW volume that are comparable to those attained for live tree volume using prism sampling, a minimum of 4 chains of sample line would be required at each sample point. This compares reasonably well with the 100m (or 5 chains) per sample point guidance of Woldendorp et al. (2004). Although this may not seem intimidating at first, consider the case of an inventory crew expected to put in 20 sample points per day. For the crew member conducting LIS, this level of sample effort adds a mile or more of additional walking per day, during which time the crew member is also conducting measurements. If the sample line is not

laid out as a closed traverse (e.g., an equilateral triangle or a square), the same length of line must be traversed again on the return.

As an extreme example, Böhl and Brändli (2007) report that under Swiss conditions establishing 30m of LIS transects in a Y-shaped cluster required 5 to 6 minutes per sample point. Although they report standard errors, they do not report sample size, so the most important information for inventory design (standard deviation or coefficient of variation) cannot be calculated exactly. However, based on approximate sample sizes calculated from their figures, we have estimated that the coefficient of variation for LDW volume must be approximately 250%. Thus, for example, to achieve 95% confidence limits of plus or minus 20% on LDW volume would require slightly more than 600 sample points, or nearly 20 km of sample line in aggregate (requiring approximately 60 hours of sampling effort). Böhl and Brändli (2007) also report that no LDW was found on 40% of sample plots, and that 10% of the sample plots contributed 50% of the total LDW volume. These results reflect the relatively sparse LDW populations in European forests, but they highlight the extreme variability of LDW and also the need for large sample sizes with LIS. The European experience with LIS should be borne in mind when considering restrictive definitions of LDW, such as those employed by the Reserve, because those definitions make LDW more "sparse" than CWD under the USFS FIA or similar definitions.

8c. Transect Relascope Sampling

Basic Description

Transect relascope sampling (TRS) was developed by Ståhl (1997, 1998) to address the sometimes excessive sampling requirements of LIS. The word "relascope" in TRS reflects the generic use of the term in European practice to indicate any angle gauge used for forest sampling; it does not in this case mean Bitterlich's Spiegel-Relascope. In TRS, one lays out a sample line (as in LIS). Logs are tallied not only if they cross the line, but also if, from any point on the line, the two ends of the log appear wider than the angle gauge. Angle gauges would have angles in the tens of degrees (versus the angles of 1 to 3 degrees used in horizontal point sampling of standing trees).


Zander Evans

The zone from which a log appears wider than the angle gauge is the union of two overlapping circles, with the degree of overlap and exact configuration of the circles depending on the angle associated with the gauge. For a given angle, however, the size of this zone (expressed in terms of its length, width, or other linear dimension) is proportional to log length, and TRS samples logs with probability proportional to their length (Ståhl 1998). Of special interest is the case where a 90-degree gauge is used: then the two circles overlap completely, and the zone for a log is just a circle, with diameter equal to log length, centered on the midpoint of the log. In this situation, log orientation becomes irrelevant to its

inclusion, so the question of log or sample line orientation disappears (Ståhl 1997).

Corrections for sloping logs or terrain are detailed by Ståhl et al. (2002). The mirage method for line intersect sampling detailed by Gregoire and Monkevich (1994) can also be applied to TRS. Ringvall et al. (2001) elaborate on the use of auxiliary information and double sampling approaches in TRS.

Required Measurements

Because TRS samples logs that do not necessarily cross the line, there is no automatic "crossing point" as there is in LIS. Thus, individual LDW pieces must be measured for volume in the same way that they would be for fixed area plots. Log length, at least one cross-sectional area (but typically more, depending on the volume equation used), and an overall decay class for the log must be measured. For sloping logs, the slope should also be recorded. Gove et al. (2002) outline multistage sampling approaches that can be used to deal with irregular and forked LDW.

Special Advantages

The principal advantages of TRS are that it augments the LDW tally over what would be obtained with LIS, so in theory fewer or shorter lines would be needed (the requirement would depend on the angle gauge used). Moreover, the obliteration of orientation assumptions by the use of a 90-degree gauge eliminates a source of bias (if sample lines are not random and inappropriate estimators were used in LIS) or variance (if sample lines were random, or estimators that incorporated log orientation were used in LIS). Thus, especially with a 90-degree gauge, there should be substantial gains in efficiency, and Ståhl (1997) presents simulation results that substantiate the claim.

Operational Challenges and Sources of Bias

Although Woldendorp et al. (2002) state that TRS and the related point relascope sampling approach outlined below require that logs be straight, their assertion is incorrect. TRS (and PRS) do require a rule for establishing which branch tip is the "end" in forked logs, but this is straightforward in practice.

More importantly, Ringvall and Ståhl (1999b) found substantial downward bias in field estimates using TRS, especially when a narrow-angle gauge was used. The bias could be associated with inappropriate use of the gauge and/or nondetection errors. They also found significant interobserver variation when small angles were used. They suggested that TRS might be most useful as the first phase in a multistage sampling effort (with later stages correcting any observer bias), and also suggest very wide angle gauges (80 to 90 degrees) when considerable LDW is present, when understory vegetation is heavy, or when approximately unbiased estimates are desired.

TRS has seen very little field testing in North American conditions. Jordan et al. (2004) report that an initial trial of TRS caused so much material to be tallied that the method was abandoned for further testing. This almost certainly reflects differences in typical LDW loadings between the European conditions for which Ståhl (1997, 1998) developed the method and those of northeastern North America where Jordan et al. (2004) were working. However, because the Reserve has defined LDW in much more restrictive terms than Jordan et al. used for CWD (their

study used a 3” minimum diameter and no minimum length), it might be worth revisiting the case of TRS with a 90 degree gauge for inventory of larger LDW.

8d. Point Relascope Sampling

Basic Description


Christopher Riely

Soon after the introduction of TRS, Gove et al. (1999) realized that an angle gauge could be used around a point to sample LDW, just as a prism typically is in sampling live trees. Point relascope sampling (or PRS) was quickly developed as an operational technique. The difference from the use of a prism is that, as in TRS, a relatively wide gauge (with an angle in the tens of degrees) is swept around the point, and the observer sights on the two ends of the LDW piece. If the piece appears wider than the gauge, then it is tallied. The zone comprised of two overlapping circles that was previously discussed in TRS becomes the inclusion zone for the log (analogous to the “imaginary circle” that surrounds trees in prism sampling), and the area of this inclusion zone is proportional to log length squared. Thus, PRS samples logs with probability proportional to size (expressed as length squared), and a given angle gauge is associated with a “length squared factor” akin to the basal area factor of a prism. Gove et al. (2001) provide a less technical overview geared toward practitioners, while Gove (2001) presents an even shorter summary.

Although PRS is derived from TRS, PRS makes no log orientation assumptions no matter what angle gauge is used. Corrections for sloping logs or terrain are detailed by Ståhl et al. (2002). Any of the standard techniques for boundary slopover correction are applicable, though because of the irregular inclusion zone shape the walkthrough method (Ducey et al. 2004) may be simplest.

Required Measurements

Just as with TRS and fixed area plots, in ordinary PRS individual LDW pieces must be measured for volume in the same way that they would be for fixed area plots. Log length, at least one cross-sectional area (but typically more, depending on the volume equation used), and an overall decay class for the log must be measured. Log length and the distance from the sample point to each end of the log is sufficient to determine whether borderline logs should be included (Gove et al. 1999). For sloping logs, the slope should also be recorded. Gove et al. (2002) outline multistage sampling approaches that can be used to deal with irregular and forked LDW.

Just as in fixed area plot sampling, in some implementations of LIS, and in TRS, the need to employ a volume equation and that of assigning an overall decay class represent sources of potential bias. To overcome these limitations, Gove et al. (2005) devised critical point relascope sampling. In this variant, the angle gauge is held so that one side aligns with one end of the log, and the position on the log that aligns with the second side is taken as a measurement point for

cross-sectional area and decay class. Gove et al. (2005) provide estimators and a simulation study examining the efficiency of aligning the gauge with the large end, the small end, or using both protocols and averaging. No published field test of critical point relascope sampling exists, however.

Special Advantages

Of the newer field methods, PRS has been the most extensively tested in North American conditions. Early tests by Brissette et al. (2003) in managed stands in Maine (including some recently harvested stands) found no detectable bias in comparison with LIS. (PRS is theoretically unbiased, so detectable bias would indicate nonsampling errors such as nondetection or measurement errors associated with the method.) Subsequent field testing in Northern hardwoods by Jordan et al. (2004) found PRS to be typically more efficient than LIS or fixed area sampling for volume, subject to concerns about nondetection if too narrow an angle was used (as outlined below). Kenning (2007) found similar results in ponderosa pine and lodgepole pine stands in Colorado, and in coastal Douglas-fir stands in British Columbia. However, it should be noted that the newer perpendicular distance sampling approach (to be described below) outperformed PRS in many of these conditions. Pesonen et al. (2009) found PRS to be the most efficient of all the methods they studied (including fixed plots, TRS, and adaptive cluster sampling; but not perpendicular distance sampling) in Finnish forests.

PRS is quite adaptable to double sampling; the two-phase approach taken by Ringvall et al. (2002) for PRS is directly analogous to the common practice of point double sampling in prism cruising. In principle, this can further enhance efficiency.


David Affleck

Operational Challenges and Sources of Bias

The choice of gauge angle (or "length squared factor") appears to be as important to successful implementation of PRS as choice of basal area factor is to prism cruising. Angle gauges that are too narrow (or, equivalently, length-squared factors that are too large) can lead to very large inclusion zones for large logs, implying that they could potentially be tallied from a great distance. This can lead to nondetection bias and/or inefficient search. For example, Jordan et al. (2004) suggest using an angle greater than 40 degrees in Northern hardwood stands, while Kenning (2007) found an angle approaching 60 degrees (actually a 57-degree angle) to work best in most of his Western study stands. A 90-degree gauge (leading to a circular inclusion zone, with diameter equal to log length) was recommended for stands with heavy slash and in old-growth coastal Douglas-fir characterized by abundant, extremely long downed LDW.

Even with an appropriate length-squared factor, PRS involves some work. Because many tallied pieces are at some distance from the sample point, PRS is most efficient with field crews of two

or three (in which one person can stand at the sample point, sight on logs with the gauge, and record, while one or two others take measurements, spot decayed or cryptic LDW, and help the sighter locate the positions of hidden ends of logs). Thus, Gove et al. (1999) suggest PRS may not be the most suitable method when cruising is being done by a lone forester or technician, as is typical in many practical situations.

8e. Prism Sweep Method (Diameter Relascope Sampling)

Basic Description

The basic prism sweep method was described by Bebber and Thomas (2003), who called it diameter relascope sampling (or DRS) to distinguish it from point relascope sampling. Like PRS, the method is centered on sample points. The cruiser uses an ordinary prism (or other angle gauge) to sight on the midpoints of downed logs. If the log is "in" (i.e., wider than the gauge, or the portions of the log overlap when viewed through the prism) the log is tallied. The estimate of volume per acre at a sample point is

$$\hat{V} = BAF \times \sum_i l_i$$

where *BAF* is the basal area factor (ft^2/acre) of the angle gauge, and the summation is over all the logs tallied at the point. To obtain number of logs per acre, one uses the midpoint diameter in place of DBH in the usual formulae for sampling live trees with a prism. The Bebber and Thomas (2003) approach implicitly uses Huber's formula for the volume of LDW pieces. Thus, while from a sampling perspective the method is design-unbiased, there is a nonsampling error in the use of Huber's formula that should typically introduce a very slight downward bias in estimates of volume. Standard techniques for dealing with boundary slopover are applicable to the prism sweep method.

We note that other researchers have adapted prism sweeps in an *ad hoc* fashion (such as sighting on the "breast height" equivalent point of downed LDW). For example, Flynn (2008) appears to have followed such an approach but the description given does not allow evaluation of the suitability of the method.

Required Measurements

In the Bebber and Thomas (2003) approach, if volume by decay class is needed to estimate LDW carbon, then the only required measurements on most tallied logs will be their length and the assignment of a representative decay class to the entire log. If number of logs per acre is also desired, then the cross-sectional area at the midpoint is needed.

For logs that are borderline, it will be necessary to measure the log length in order to find the midpoint accurately, then the cross-sectional area at the midpoint should be measured (and, if not assumed circular during measurement, converted into an equivalent diameter), and finally the distance from the log midpoint to the sample point should be measured and compared to a conventional limiting distance table for the BAF being used. It may be difficult to determine whether or not to include heavily decayed logs that depart substantially from a circular cross-section; one should also treat these logs as "borderline," rather than relying on the angle gauge.

Special Advantages
The prism sweep method uses tools that are familiar to field foresters, which should facilitate training and help mitigate against field errors. For example, Bebber and Thomas (2003) used a BAF 2 m^2/ha (8.7 ft^2/ac) prism in their original field trial, and write (p. 1,742), "Use of the same prism for standing trees and CWD seems a reasonable and convenient practice." Bebber et al. (2005) employ a similar approach with the same BAF, while Osborne et al. (undated) suggest that the same BAF could be used as that for standing trees, but do not indicate what was used in their trials. The Bebber and Thomas (2003) approach is statistically very efficient when log midpoint diameter and log length are well-correlated. That is most likely to be true in circumstances where much of the volume is in relatively intact pieces (e.g., whole trees), and less so when LDW is composed of cut or broken pieces (tops, chunks, and slash). Nonetheless, Osborne et al. (undated), working in a recently harvested site in North Carolina, report that prism sweeps were more time-efficient than LIS. The study by Osborne et al. (undated) is the only known study providing time estimates for the method.

Operational Challenges and Sources of Bias
As a visual search method, the prism sweep approach can encounter challenges with visibility. These could be mitigated by choosing a larger basal area factor, but we know of no study examining the operational bias and efficiency of this approach as BAF is varied. As previously mentioned, the use of Huber's equation to estimate volume introduces a bias of uncertain sign and magnitude into volume estimates, though this bias is likely to be less than what would result from using, say, Smalian's formula. Finally, it is not immediately obvious how one should deal with forked LDW in the prism sweep approach, but it should be possible to devise reasonable protocols.

8f. Perpendicular Distance Sampling

Basic Description
Perpendicular distance sampling (PDS) was developed, in its original form, by Williams and Gove (2003) as a probability proportional to volume sampling method: estimates of volume per acre could be obtained by a simple count of logs without any measurements whatsoever on the logs (except in borderline cases). Williams et al. (2005a) generalized PDS to sample with probability proportional to surface area, while Williams et al. (2005b) detailed slope correction and methods for dealing with crooked or forked logs.


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In the original version PDS, the cruiser establishes a sample point, then sights on downed LDW pieces at their "perpendicular point"—the point on the log at which our line of sight is perpendicular to the log axis. Logs are included in the tally only if they are closer than a critical

distance that is proportional to cross-sectional area. The volume per acre is just the number of logs tallied times a volume factor that depends on the proportion between critical distance and area. The volume factor plays the same role in PDS that the basal area factor does in prism sampling. Because an ocular estimate of approximate diameter and distance, coupled with a simple table, is sufficient to determine whether most logs should be included or not, very few logs require any measurement at all.

Early in the development of PDS, it was recognized that having the critical distance strictly proportional to cross-sectional area meant that "runaway" critical distances would occur for large downed LDW. This would have necessitated a time-consuming search (which would have sabotaged the efficiency of the method), entailed nondetection errors, or both. Thus, the method was modified to include a maximum critical distance irrespective of diameter at the perpendicular point. The maximum critical distance is set based on expected visibility conditions within the stand (for example, 1 chain in stands with relatively open understories and one-half chain in stands with dense understories or where travel is difficult because of slope). This "distance-limited PDS" approach is outlined in a short paper for practitioners by Ducey (2007), which is unfortunately not widely available. The method was implemented successfully in early field trials in New England (Ducey et al. in review) and subsequently in Western forests by Kenning (2007). The modified method is briefly described by Valentine et al. (2008), and in slightly greater detail in an extension paper by Roberge (undated). Ducey et al. (in review) provide proofs of unbiasedness for distance-limited PDS. Distance-limited PDS is the currently recommended form of PDS for practical LDW inventory.

Required Measurements

In the original version of PDS, no measurements are needed on LDW pieces that are obviously close enough in their cross-section, or equivalently large enough in their distance from the sample point, that they should be included in the tally. Decay class is only needed at the perpendicular point. In distance-limited PDS, this remains true for pieces with size at the perpendicular point small enough that the cross-sectional area determines the critical distance. For these pieces, if a log is borderline, the cross-sectional area at the perpendicular point and the distance from the sample point to the perpendicular point should be measured. No log length is needed.

In distance-limited PDS, if a log is large enough at the perpendicular point that the maximum critical distance is in effect, then the cross-sectional area at the perpendicular point is needed even if the log is close enough that it clearly should be tallied. However, in practice this usually only occurs for a small fraction of tallied logs. For example, the data presented in Valentine et al. (2008) were originally tallied using a volume factor of 200 ft^3/ac and a maximum critical distance of 66 feet, but out of more than 30 logs tallied on 18 points, none required invoking the maximum critical distance.

The walkthrough method (Ducey et al. 2004) is the simplest slopover correction method with PDS. As Williams et al. (2005b) discuss, all cross-sectional area measurements are assumed to be taken in a vertical plane (or corrected trigonometrically to the vertical plane) if the log is inclined on a slope. Ducey et al. (2008) demonstrate that if log length and cross-section at the

perpendicular point are measured, PDS or distance-limited PDS can also be used to estimate a wide range of log characteristics (including pieces per acre and surface area coverage).

Special Advantages

Because distance-limited PDS tallies smaller LDW with probability proportional to size, and larger LDW with probability proportional to length, it is an extremely fast method in the field, typically requiring 1 to 2 minutes per sample point when implemented by experienced timber cruisers who can estimate diameters and distances with reasonable accuracy. Its probability proportional to size nature also provides fairly low variance considering the small number of pieces tallied per point, and at operationally reasonable volume factors. Moreover, because it does not depend on any assumption about taper rate, it automatically and completely eliminates the biases that attend other methods depending on volume formulae (such as Smalian's or Huber's).

In the most extensive field testing of distance-limited PDS, Kenning (2007) found that the method was the most efficient of all those tested, bested only in a few cases by PRS. PDS easily outperformed LIS in nearly all cases, echoing the early New England field trial results (Ducey et al. in review). Moreover, PDS is eminently suitable for work by a single cruiser. For example, one person working alone collected the 18 sample points reported by Valentine et al. (2008) from a riparian forest fragment in approximately 1 hour, including initial reconnaissance and time spent walking between sample points. The resulting 95% confidence limits were plus or minus 30% of the mean. Such results with so little effort compare quite favorably with what one might reasonably expect using, say, LIS.

Operational Challenges and Sources of Bias

The efficiency of distance-limited PDS depends critically on rapid and effective visual search. Thus, it is important to choose a reasonable maximum limiting distance in order to avoid unnecessarily long search times (or, conversely, an unacceptable risk of nondetection) for large-diameter logs. For example, Williamson (2008) employed PDS without a maximum limiting distance in forests in Maine and, in an effort to eliminate nondetection error, incurred exorbitant sampling time costs. It is also true that PDS becomes quite inefficient when cruisers cannot estimate diameter (or cross-sectional area) and distance ocularly, so that a large number of pieces require checking because they are "borderline."

8g. Line Intersect Distance Sampling

Basic Description

Line intersect distance sampling (LIDS) is perhaps the newest LDW method (Affleck 2009a). It combines the simple linear search strategy of LIS, which is associated with low nondetection error, with the probability proportional to size attributes of PDS. In LIDS, one or more sample lines are laid out radially from an initial sample point. Only LDW pieces that cross the sample line are candidates to be tallied. Furthermore, LDW pieces are only tallied if they are closer to the sample point than a critical distance that is proportional to cross-sectional area at the sample line. This results in a probability proportional to volume selection procedure that avoids the potentially challenging radial search associated with PDS. Affleck (2009b, 2010) found that although LIDS required more sample time per point than LIS (which was employed in a fashion

similar to the FIA design), LIDS offered an increase in efficiency by concentrating sample effort on pieces that contributed more to volume estimates.

Required Measurements

Similar to the original implementation of PDS, LIDS requires actual measurements only for those logs that are "borderline," i.e., for those whose cross-sectional area is not obviously greater than that needed for inclusion at their distance from the sample point. A simple count of LDW pieces by decay class gives the raw data for volume (and eventually carbon) by decay class. For borderline pieces, cross-sectional area and distance along the sample line should be recorded. Affleck (2009a) reports implementing LIDS using the reflection method of Gregoire and Monkevich (1994).

Special Advantages

LIDS appears to combine the low nondetection bias of LIS with the theoretical efficiency of PDS. Although no direct time comparison between the two methods has been published, LIDS does not appear to be as fast as PDS, in part because of line travel requirements. However, the time cost may be compensated by the elimination of nondetection bias in problematic sampling environments.

Operational Challenges and Sources of Bias

LIDS is a robust and efficient strategy for LDW inventory, but as one of the newest methods it also has not seen widespread field testing. Further work will be needed to establish its efficiency relative to other methods, to substantiate its apparent advantages in difficult environments, and to estimate likely costs over a range of conditions. However, based on its early performance it should be considered a serious contender for assessing LDW carbon.

9. Field Comparisons and Operational Costs

Careful comparison of methods in the field, including timed studies to establish relative costs, is an expensive undertaking. Absent a vigorous carbon market or voracious demand for biomass, LDW is not a financially valuable asset. Thus, it should come as no surprise that there are very few studies that compare LDW sampling methods under North American conditions or, for that matter, anywhere. Furthermore, the costs of any LDW method depend on multiple factors, including the abundance, size, structure, and decay status of LDW, as well as stand structure (especially as it impacts visibility), topography, crew characteristics (including training and aptitude), and equipment used. Nonetheless, some patterns do emerge from the few studies that have reported both sample variability and time costs for one or more LDW methods. These include Jordan et al. (2004), Böhl and Brändli (2007), Kenning (2007), Pesonen et al. (2009), Affleck (2009b, 2010), and Osborne et al. (undated). Bate et al. (2002) present partial information, but key information (such as time requirements) is not given quantitatively. The methods employed in each study are summarized in Table 6. Key points include the following:

1. Most studies report that fixed area plots and strips are extremely time-consuming (10 minutes to half an hour for a 0.2-acre plot) and yield high variances for volume.
2. Line intersect sampling has a considerable fixed setup cost, whether or not much if any LDW is present. Thereafter, it is slightly faster than fixed area searches (depending on the amount of line per sample point; 3 to 5 minutes per chain of line may be a reasonable

figure under many conditions, with 2 to 5 chains of line per sample point) and substantially more efficient.

3. Both PRS and the prism sweep method are faster still than LIS, though possibly more variable (requiring an average of 3 to 10 minutes per sample point), and have variance characteristics that make them competitive with or better than LIS. However, nondetection may be a concern, and (in the forms that have been tested) PRS and the prism sweep methods may include some bias due to log volume measurements.
4. PDS is very fast (1 to 2 minutes per sample point) and very efficient, though many points may be needed to achieve narrow confidence limits and nondetection is a concern in adverse conditions.
5. LIDS requires more time than LIS (perhaps by a factor of 50%) but results in lower variance because of its sampling characteristics, so it is more efficient.

Note that the time requirements given above are approximate, and will be heavily influenced by sampling conditions. For example, both Kenning (2007) and Affleck (2009b, 2010) report LIS time requirements that exceed those given here, and Kenning (2007) reports a strong topographic influence on time requirements for other methods as well. Given the paucity of published papers that provide time estimates for different methods, we would encourage those planning an LDW inventory to conduct a pilot study to estimate costs before embarking on a full campaign.

Table 6 Studies reporting variability and time costs for LDW sampling

Study	*Conditions*	*Fixed Area*	*LIS*	*TRS*	*PRS*	*Prism Sweep*	*PDS*	*LIDS*
Bate et al. 2002	Western conifers (eastern OR, western MT)	X	X					
Jordan et al. 2004	Northern hardwoods (NH)	X	X		X			
Böhl and Brändli 2007	Various (Switzerland)		X					
Kenning 2007	Western conifers (CO, BC)	X	X		X		X	
Pesonen et al. 2009	Boreal forests (Finland)	X	X	X	X			
Affleck 2009b	Western conifers (MT)		X					X
Affleck 2010	Western conifers (MT)		X					X
Osborne et al. undated	Recently harvested (NC)		X			X		

10. Modeling Approaches

As an alternative to field measurement, it is reasonable to consider modeling approaches, especially those that are based on statistically representative field data for particular regions and/or forest types. Although a great many models have been developed for predicting different attributes of forests in North America, we consider here only those that have a coherent nationwide framework, include specific information for carbon accounting, and have a documented connection to field data collected over a large proportion of the continent. These include the regional lookup tables and related procedures of Smith et al. (1996), the COLE/GCOLE suite of online tools (NCASI 2007), and the new carbon accounting capacity of the Fire and Fuels Extension of the Forest Vegetation Simulator (FVS) (Hoover and Rebain 2008, Reinhardt et al. 2009).

Smith et al. (2006) present methodology and representative tables for major carbon pools of forests in the United States, with separate tables for afforestation and reforestation by major forest types. Estimates for the majority of carbon in pools represented in the tables are derived from the USFS Forest Inventory and Analysis (FIA) data. Although most common productive forest types in the U.S. are represented in the tables, some rare types may not be. These tables represent an accepted form of carbon stock estimation for 1605(b) reporting. The tables are not intended to accommodate uneven-aged stands or designed to be sensitive to subtle differences in management strategy (such as responses to LDW retention guidelines). However, they do represent defensible regional averages for common forest types. Smith et al. (2006) also detail methods for localizing the tables, for example by replacing average live tree volume yield curves with curves derived from location- or project-specific data.

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There are three main difficulties with using the Smith et al. (2006) tables (or localizations of them). First, the application of the Smith et al. (2006) tables to reporting at a detailed level (e.g., separate pools, consistent with Reserve definitions) requires additional, field-based calibration and adjustment. Second, the tables from Smith et al. (2006) are not intended to accommodate uneven-aged stands, which are common under the Reserve's protocols. The third difficulty is that the definition of the "down dead wood" (DDW) pool in their work is not commensurate with the definition of LDW put forth by the Reserve. Smith et al. (2006) parallel the FIA definition, which considers all fallen woody necromass with a diameter of 3" or greater to be DDW. By contrast, the Reserve defines LDW as having a minimum diameter of 5" and a minimum length of 8'. Thus, the Smith et al. (2006) tables include material that has a smaller diameter, a shorter length, or both. Naive application of the Smith et al. (2006) tables to estimate LDW carbon for Reserve projects will result in overestimates, and lead to flawed analyses if those estimates are subsequently compared to field measurements that do conform to Reserve definitions. Differences between DDW and LDW should be expected to depend on region, forest

type, forest management, and past disturbance history, as all of these factors will influence the proportion of DDW that is in material less than 5" in diameter, less than 8' in length, or both (as outlined in Chapter 1). From a certain perspective, the discrepancy between DDW and LDW is unimportant because DDW that is not LDW should be included in the litter pool, as defined by the Reserve. However, if carbon stocks are to be reported in a transparent fashion, the discrepancy must be acknowledged.

The COLE and GCOLE online estimators (NCASI 2007) are designed to provide intuitive, straightforward access to carbon estimates based on FIA data, including the generation of 1605(b) reporting tables. However, COLE and GCOLE share common estimation procedures and definitions for DDW with the Smith et al. (2006) tables. Therefore, all of the limitations and caveats associated with using the Smith et al. (2006) tables, including the need for field-based calibration and adjustment for consistent reporting of individual carbon pools, are also relevant for COLE/GCOLE.

Some of the limitations of the Smith et al. (2006) tables, or the COLE/GCOLE (NCASI 2007) approach, can be overcome by incorporating LDW carbon directly into individual-tree growth and yield modeling by accounting for modeled trees post-mortem. However, at this time there is only one nationally-consistent modeling framework for U.S. forests, the Forest Vegetation Simulator (FVS): www.fs.fed.us/fmsc/fvs. FVS is not a single model, but rather a collection of modeling tools built on a shared mathematical and computational framework. The Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003) was recently modified to provide direct accounting for carbon in multiple forest pools (Hoover and Rebain 2008, Reinhardt et al. 2009). With this added capability, FVS can be used to simulate stand growth and carbon sequestration of forest stands, including responses to silvicultural interventions (Hoover and Rebain 2008, Hurteau and North 2009, Reinhardt and Holsinger 2010). However, FVS follows FIA (Woodall and Williams 2005), the tables of Smith et al. (2006), and COLE/GCOLE (NCASI 2007) in defining DDW in a manner consistent with the diameter threshold for 1,000-hour fuels in fire modeling (i.e., material 3" in diameter or larger). FVS has limited ability to break out the diameter of fuels (or DDW/LDW) beyond the size thresholds required for typical fire behavior models. Therefore, the limitations and caveats noted above, which follow from the definitional inconsistency between FIA DDW and Reserve LDW, apply to FVS. Furthermore, although testing and comparison of the carbon capabilities of FVS with field data have been performed for a small number of experimental forests or forest types (Hoover and Rebain 2008, Hurteau and North 2009, Reinhardt and Holsinger 2010), no widespread validation study has been published. A national-scale evaluation and comparison study is underway, but results from that study are not yet available, and do not address LDW as defined by the Reserve. Thus, while FVS is a very useful tool for analysis and projection of forest carbon stocks, its use to project carbon in LDW should be considered cautiously and in conjunction with field-based calibration where possible.

Conclusions: Because the definitions of DDW in Smith et al. (2006), COLE/GCOLE, and FVS are all consistent with FIA definitions, and because LDW as defined by the Reserve is strictly a subset of FIA DDW, it should be possible (in principle) to conduct a region- and/or forest-type-specific examination of differences using existing FIA field data. Such an analysis could, at least potentially, lead to tables similar to those of Smith et al. (2006) but which provide regional (or type-specific) averages for LDW carbon that are consistent with Reserve definitions. However,

we caution that the analysis is not entirely straightforward, in part because FIA data do not include the length of LDW pieces to the 5" minimum diameter. Thus, assumptions about LDW taper and appropriate handling of LDW inclusion probabilities would require attention. Done improperly, such an analysis could lead to erroneous conclusions about the portability of those modeling tools to the Reserve framework.

10. Conclusions

Measuring LDW is time consuming and presents some unique challenges. The number of LDW pieces per acre may be large, but usually only a few of them contribute substantially to the carbon pool. Breakage, orientation, and decay all present challenges, and because LDW is typically on or near the ground it can be obscured by understory vegetation, moss, or litter. The payback for overcoming the challenges to accurately measure LDW is typically low in terms of total forest carbon (see Figure 3). Live trees usually contain more carbon than LDW and are more easily measured.

The in-depth discussion of sampling methods in section 7 shows that there is no perfect method for sampling LDW. Each method has some advantages (see Table 5), and each has advantages for particular LDW characteristics. Any of the methods discussed here could be used to compare initial baseline LDW carbon with actual evolution of LDW carbon following project implementation. However, given the limited cost or time estimates for LDW measurement currently available, project managers should conduct a pilot study to estimate costs before committing to a full campaign. Some of the new sampling methods discussed here, such as PDS or LIDS, hold promise for more efficient sampling of LDW as they become more widely tested and practiced.

Modeling LDW has some of the same challenges as field measurement, compounded by the differences in definition between Reserve definitions of LDW and the definitions employed by the most widely used modeling tools. Modeling the buildup or loss of LDW over time is hampered in part by that fact that it is a relatively new interest compared to modeling tree growth. Another challenge in modeling LDW is the U-pattern LDW often follows during stand development, unlike tree growth which often follows a pattern of linear increase. A key input to any model of LDW change over time is the initial quantity of LDW. As discussed in Chapter 1, LDW, snags, or logging slash from the previous stand determine LDW quantities for a substantial portion of stand development, and assumptions about breakage and utilization can be critical for predicting the LDW content of managed forests. Decay of LDW is another challenging element of model development, as illustrated by the wide range of decay rates mentioned in Section 3b. Hopefully, this review of the current state of the science of measuring LDW will help to advance the field.

11. Definitions

Chronosequence: A sequence of forest stands of different ages but otherwise similar in site attributes such as soils, precipitation, and composition.

Coarse woody debris (CWD): Down dead wood with a small-end diameter of at least 3" and a length of at least 3'.

Lying dead wood (LDW): Any piece(s) of dead woody material from a tree, e.g., dead boles, limbs, and large root masses, on the ground in forest stands. Lying dead wood is all dead tree material with a minimum average diameter of 5" and a minimum length of 8'. Anything not meeting the measurement criteria for lying dead wood is considered litter. Stumps are not considered lying dead wood.

Salvage harvest: The removal of trees damaged, dying, or dead because of insect outbreak, pathogen, fire, wind storm, or other event.

Selection system: A planned sequence of treatments designed to maintain and regenerate a stand by removing trees either singly or in groups and allowing for regeneration.

Snags: Standing dead trees.

Suppressed tree: A tree overtopped by surrounding trees which is usually growing slowly and often in poor health.

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