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# Development of a Downed Woody Debris Forecasting Tool Using Strategic-Scale Multiresource Forest Inventories

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The increasing interest in forest biomass for energy or carbon cycle purposes has raised the need for forest resource managers to refine their understanding of downed woody debris (DWD) dynamics. We developed a DWD forecasting tool using field measurements (mean size and stage of stage of decay) for three common forest types across the eastern United States using field observations of DWD from the US Department of Agriculture Forest Service's Forest Inventory and Analysis program. Residence times for DWD ranged from as short as 20.3 ± 9.7 years (mean ± SD) for loblolly pine biomass in the southeastern United States to as long as 41.7 ± 20.9 years for aspen biomass in the Lake States. Although we suggest numerous improvements through refined DWD measurements and models, our proposed tool can be considered a rapid assessment technique to assist natural resource managers in forecasting DWD populations. Beginning with using log size and decay stage to understand deadwood dynamics, future researchers should seek to refine DWD metrics through implementing enhanced forest inventory information and exploring the impacts of forest disturbances on inputs to the DWD pool.

**Keywords:** coarse woody debris, Forest Inventory and Analysis, decomposition, forest management, wildlife management

More than 2.6 trillion pounds of carbon are found in the coarse woody debris component of the downed woody debris (DWD) pool across US forests (Woodall et al. 2013). Information on DWD, defined as downed deadwood ≥3.0 in. in diameter and ≥3.0 ft in length, is critical for determining the suitability of forest structural attributes for deadwood-dependent wildlife and other organisms, estimating forest fuel loads, and understanding its fate in the context of the forest carbon balance. A number of forest management guidelines highlight specific recommendations for sustaining and/or creating deadwood (Benjamin 2010, Minnesota Forest Resources Council 2012, Virginia Department of Forestry 2011), and forest certification programs explicitly list DWD in performance measures for promoting sustainable forestry (Sustainable Forestry Initiative 2015). Recent concerns on the role of deadwood from a forest carbon accounting perspective (e.g., Miner et al. 2014, Ter-Mikaelian et al. 2015) showcase the role that this pool plays in the global context of greenhouse gas emissions associated with decomposing wood.

The majority of research to date has emphasized efficient methods for sampling woody debris and determining their stocking levels. Line intersect sampling (Warren and Olsen 1964) has existed for more than 50 years and continues to be a widely used method for efficiently determining current stocks of DWD residing on the forest floor. Used by the US Department of Agriculture (USDA) Forest Service's Forest Inventory and Analysis (FIA) program for more than a decade (Woodall et al. 2011), information obtained from line intersect samples could seemingly be used as a surrogate for determining future DWD populations.

Despite the vast amount of information available on technical approaches to quantifying DWD (e.g., Russell et al. 2015), much less research has been devoted to the development of practical tools that allow resource managers to forecast DWD populations through time. In the context of stand dynamics, inputs to the DWD pool arise from tree mortality as a result of forest disturbance and self-thinning in addition to the senescence of living trees (e.g., branch fall and breakage). Harmon (2009) showed that

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temporal patterns after disturbance could exhibit a U-shaped, reverse-J, S-shaped, or mixed-shaped pattern. Inherent to these curves, deadwood diminishes though time after processes such as decay and harvesting. In terms of DWD stocks, the ratio of DWD (including coarse and fine woody debris and residue piles) to total standing tree biomass can vary considerably, ranging from 0.07 to 0.37 (Woodall et al. 2013). Woodall and Westfall (2009) define the "deadwood stocking conundrum zone" as a conceptual area where DWD stocking is difficult to predict using live-tree attributes alone; that is, DWD stocks may show little correlation in forests with average live-tree densities. One approach to refine our knowledge of DWD stocking is to seek the development of management tools depicting DWD dynamics that are dependent on forest type and stand/site conditions.

The overall objective of this study was to use compiled estimates of residence times and observations of DWD to develop a forecasting tool for DWD biomass. Specific objectives were to use average diameter and the percentage of wood in a two-class decay stage system as an indicator of DWD residence time (years) for three common forest types in eastern US forests and to use recent observations from the FIA program's down woody materials indicator to forecast populations of DWD biomass using the deadwood forecasting tool that we developed.

## Methods

### FIA Data

As a part of the USDA Forest Service's FIA program, permanent sample plots are established using a three-phase inventory (Bechtold and Patterson 2005). Field crews visit these plots, of which one forest inventory plot is established for an approximate 6,000-acre hexagon, to collect a base sample of inventory information on forest type, forest structure, species composition, and other variables. On a subset of plots (approximately 1 every 96,000 acres), field crews measure various components of forest ecosystem health, including DWD such as coarse and fine woody debris and forest soils (Woodall et al. 2011). For this analysis, all data were obtained from the FIA data access website (USDA Forest Service, 2014b).

Although DWD is defined in the FIA program as a more general pool of woody debris including coarse and fine woody debris and residue piles, for the purposes of this study we will be considering DWD to only include the coarse woody debris portion of FIA's more inclusive definition (Woodall and Monleon 2008). We assume that the residence time of fine woody debris is relatively short compared with that of DWD and hence focus this initial exploration solely on woody debris greater than 3.0 in. The FIA program defines DWD as dead woody pieces in forested conditions with a diameter greater than 3.0 in., a length of at least 3.0 ft, and a lean angle greater than 45° from vertical (Woodall and Monleon 2008). Hence, DWD is typically categorized as 1,000+-hour fuels using a lag-time fuel-class system (Deeming et al. 1978). All DWD pieces were sampled along three 24-ft transects using line intersects from each of four subplots. Data collected for every DWD piece includes attributes such as transect and small- and large-end diameters, length, decay class, and species. Length is defined as the total length of the DWD piece between the small- and large-end diameter measurements. A decay class of 1 indicates the least decomposed whereas a decay class of 5 is an extremely decomposed log (Harmon et al. 2008). To enable development of a parsimonious DWD forecasting diagram in this study and to avoid discrepancies in designating decay classes in the field, the 5-stage decay class system was further collapsed (Woodall et al. 2009). Hard decay pieces were categorized as all pieces in decay classes 1 and 2, whereas soft decay pieces were in decay classes 3, 4, and 5.

The loblolly-shortleaf pine (*Pinus taeda*/*Pinus echinata*), spruce-fir (*Abies-Picea*), and aspen-birch (*Populus-Betula*) forest type groups are three of the largest occurring in the eastern United States as measured in forest and woodland area, representing 22.9 million acres in the Southeast, 7.8 million acres in the Northeast, and 12.9 million acres in the North Central regions (Oswalt et al. 2014). For the purposes of this study, the most recent DWD measurements (2001–2011) were obtained for three primary species groups occurring in three geographic regions across the eastern United States. The loblolly pine species group consisted of 1,358 DWD observations from the states of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia. The spruce-fir group was composed of red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) records (a total of 1,015 observations) obtained from the states of Maine, New Hampshire, New York, and Vermont. The aspen species group consisted of 840 DWD observations of quaking (*Populus tremuloides*) and bigtooth aspen (*Populus grandidentata*) and balsam poplar (*Populus balsamifera*) from Michigan, Minnesota, and Wisconsin.

## Development of Downed Deadwood Forecasting Tool

Recent work has characterized the residence times of tree species occurring in the eastern United States (Russell et al. 2013, 2014b). With use of repeated DWD measurements from the FIA program, ordinal regression techniques were used to determine the probability that a DWD piece would remain in the same decay class or transition into more advanced decay classes over 5 years (Russell et al. 2013). With those estimates of DWD decay class transitions, the half-life and residence times for 36 east-

### Management and Policy Implications

Downed woody debris (DWD) is an integral component of forest health and is of interest to managers involved in forest management, wildlife habitat, and forest fuel assessment and fire risk. The presence and abundance of woody debris encourages biodiversity by serving as cover and habitat for deadwood-dependent plants and animals. To date, the majority of research has focused on how to accurately assess forest DWD attributes at a given time period. Our study highlights the ability to inform DWD dynamics through the development of a forecasting tool that allows managers to forecast woody debris populations. We estimated shorter residence times in southeastern US forests than in northern forest types. Through a rapid assessment of average deadwood diameter and stage of decay, trends in future deadwood stocks can be understood. Applying these results can aid natural resource managers in meeting management objectives and policy requirements that seek to maintain and/or promote the abundance of forest DWD. These results can enhance the value of using existing forest inventory information to provide insights into future forest composition and structure as a part of forest management plans.

Table 1. Summary statistics for DWD piece characteristics obtained from the down woody materials program for three eastern US forest types.

| Forest type | No. of DWD pieces | | Diameter (in.) | | | Length (ft) |
|---|---|---|---|---|---|---|
| | Hard decay* | Soft decay | Small-end | Transect | Large-end | |
| | | | . . . . . . . . . . .(in.) . . . . . . . . . . . | | | |
| Loblolly-pine (Southeast) | 249 | 1109 | 4.3 (2.2) | 5.9 (3.1) | 7.1 (3.8) | 16.6 (11.8) |
| Spruce-fir (Northeast) | 300 | 715 | 4.1 (1.7) | 5.5 (2.3) | 6.8 (2.8) | 18.9 (16.1) |
| Aspen (Lake States) | 351 | 489 | 4.4 (2.1) | 6.2 (3.1) | 7.6 (3.9) | 21.0 (16.7) |

Data are means (SDs).
* Hard decay pieces are decay classes 1 and 2; soft decay pieces are decay classes 3, 4, and 5.

ern US tree species were estimated using decay rate functions for DWD biomass and carbon (Russell et al. 2014b). Rather than relying on decay class transitions and decomposition models to quantify DWD dynamics, forest and natural resource managers could benefit from the development of a forecasting tool to characterize the complexities of deadwood decomposition.

As the longevity of DWD is complex, representing a gradual transition that is not necessarily marked by a distinct endpoint (Mackensen and Bauhus 2003), residence times are defined as the number of years in which a DWD piece loses its structural integrity and no longer meets the criteria for being sampled in a deadwood inventory (Russell et al. 2014b). From the perspective of woody debris in the FIA program, residence times can be attained when woody pieces have become incorporated into the soil or have decomposed into fine woody debris pools. Residence times for the deadwood forecasting tool were calculated by completing three primary steps. First, liberal and conservative estimates of residence times that were dependent on species and DWD size were obtained from Russell et al. (2014b). Estimates of residence times are defined as the number of years in which the mean proportion of biomass remaining for a DWD piece falls within 2 standard errors (SE; in the case of a liberal residence time) and 1 SE (in the case of the conservative residence time) of the mean for decay class 5 DWD (Russell et al. 2014b). The use of decay class 5 as an indicator for DWD biomass residence time relies on the characteristics of wood in this stage of decay having no structural integrity, no longer maintaining its shape, and spreading out on the forest floor (Woodall and Monleon 2008). For the primary species considered in this analysis, conservative residence times ranged from as short as 46 years for loblolly pine to as long as 105 years for aspen species. These residence times do not necessarily reflect steady-state dynamics as might be captured with a negative exponential decomposition curve (e.g., Olson 1963) but rather rely on field observations as DWD transitions through each of FIA's five decay classes (Russell et al. 2013). As the endpoint of decomposition is nearly impossible to note, residence times reflect general biomass loss patterns as within a forest carbon accounting framework.

Second, it was assumed that stands displaying a large percentage of deadwood in hard decay stages (i.e., greater than 67%) could be categorized as recent inputs of DWD relative to logs that have been on site potentially for decades in soft decay stages. It was assumed that these logs in hard decay stages would decompose for a duration that closely matches the complete residence time for the species of interest. We assigned the minimum diameter of the forecasting tool to 3.0 in. to align with the FIA DWD inventory and the designation of 1,000-hour fuels in fire behavior models (e.g., Anderson 1982). A maximum diameter of 24.0 in. encompasses a majority of the DWD pieces inventoried in the FIA data (e.g., Table 1). We present the forecasting tool in 3-in. diameter classes for parsimony and ease of use after completion of DWD inventories.

Last, smaller-sized deadwood (in terms of average DWD diameter) was assumed to display a shorter residence time than larger-sized deadwood. Hence, residence times for pieces in moderate and soft decay stages were predicted to occur 50 and 30% quicker, respectively, than DWD in hard decay stages. The means of both liberal and conservative residence times were calculated for each decay stage and diameter class. As an indicator of uncertainty, liberal and conservative residence times were calculated at each decay stage and diameter class (Supplemental File S1).[S]

## Using FIA Data to Forecast Deadwood Residence Time in Eastern US Forest Types

For the purposes of analyzing DWD where observations for the species of interest were common, only FIA plots where a minimum of four DWD observations were recorded for the species of interest were used to determine residence times with the developed DWD forecasting tool. This approach aligned the species-specific residence times to be applied more broadly to the forest type of interest. The totals were 100, 100, and 87 FIA plots for the loblolly pine, spruce-fir, and aspen species groups, respectively (Figure 1).

We forecast the residence times of DWD observations from FIA's DWD inventory using the forecasting tool for each of the three forest types (Figure 2). We calculated the average transect diameter for each plot as an indicator of DWD size. With use of the average DWD diameter, the percentage of DWD in a hard decay stage, and the guide (Figure 2), the residence time of DWD on each FIA plot was computed. Means and SDs were then summarized for each forest type to obtain DWD residence times for these primarily even-aged forest types. As an application to determine the attributes of future DWD given the input of standing dead trees, we apply the tool to forecast 50 years with assumptions regarding standing dead tree dynamics. Standing dead trees in moderate and hard decay stages were assumed to enter the DWD every 10 years for each of the three forest types. Nine to 12 in. diameter DWD was assumed to enter the pool in years 10 and 20, 12 to 15 in. DWD in years 30 and 40, and 15 to 18 in. DWD in year 50.

## Results

Smaller-sized DWD exhibited a shorter residence time than larger DWD, which resulted in as much as a 31% difference in residence times for small-diameter (3–6 in.) and large-diameter (21–24 in.) aspen in hard decay stages. For stands with 33–67 and less than 33% deadwood in hard de-

[S] Supplementary data are available with this article at http://dx.doi.org/10.5849/jof.15-113.

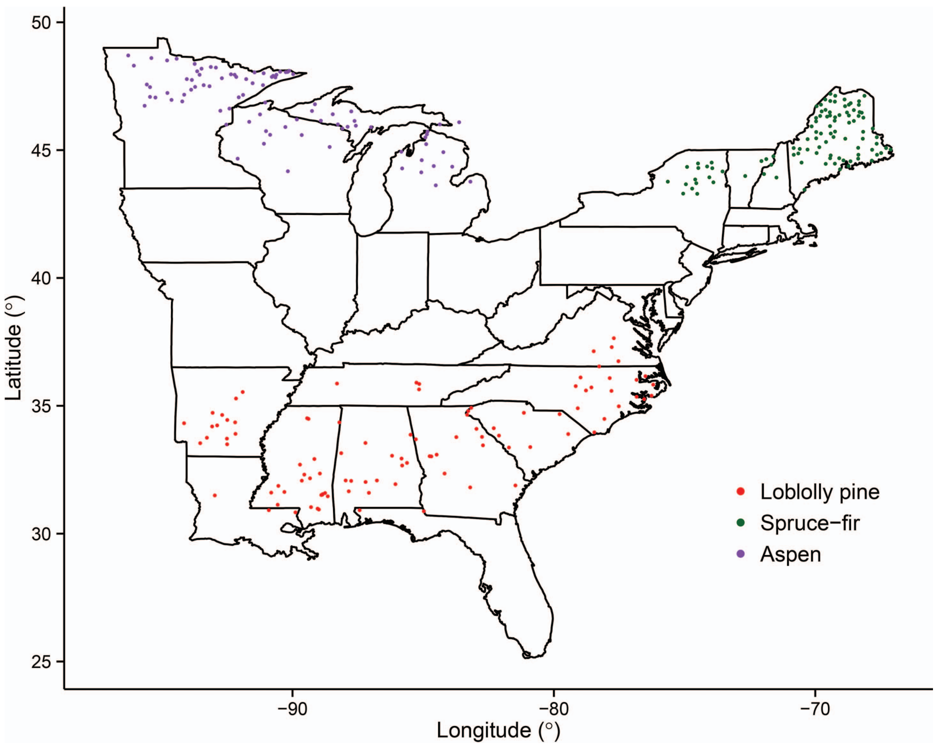


**Figure 1. Approximate locations of FIA down woody material indicator plots across three eastern US forest types, 2001–2011.**

cay stages, residence times were 50 and 33% shorter, respectively, than for stands with greater than 67% of deadwood in hard decay stages. For the same diameter and amount of DWD in a specific stage of decay, the forecasting tool indicates that residence times are shortest for loblolly pine, followed by aspen and spruce-fir (Figure 2).

Observations of DWD in decay classes 3, 4, and 5 (i.e., soft decay pieces) outnumbered those of hard decay pieces (i.e., decay classes 1 and 2) (Table 1). The percentages of DWD in soft decay stages were 82, 70, and 58% for loblolly pine, spruce-fir, and aspen forest types, respectively. Mean ± SD diameter at transect was 5.9 ± 2.9 in., and length was 18.7 ± 15.1 ft for all DWD observations and all species. With use of the tool to forecast current populations of deadwood using the down woody materials indicator data, results indicated that the average residence times of DWD for all FIA plots were 17.7 ± 8.4, 33.4 ± 16.4, and 35.1 ± 17.6 years for the loblolly pine, spruce-fir, and aspen forest types, respectively. An increasing proportion of DWD in a soft decay stage resulted in a shorter residence time of deadwood in the FIA plots. Residence times ranged from as short as 13.8 years for loblolly pine with less than 33% of deadwood in a hard decay stage ($n = 75$) to as long as 70.1 years for spruce-fir with greater than 67% of deadwood in a hard decay stage ($n = 15$) (Figure 3).

Assuming that standing dead trees would enter the DWD pool as a stand advances in development, simulations indicated that residence times would be longer as standing dead trees would be larger in diameter. For hard decay pieces entering the DWD pool at age 50, the forecasting tool indicated that these woody pieces would be depleted by ages 100, 130, and 130 for the loblolly pine, spruce-fir, and aspen forest types, respectively. Compared with DWD at initial conditions, residences were 50, 80, and 70 years for these same forest types (Figure 4).

## Discussion

Although there has been a large volume of research on inventory methods and application in assessing DWD stocking (Russell

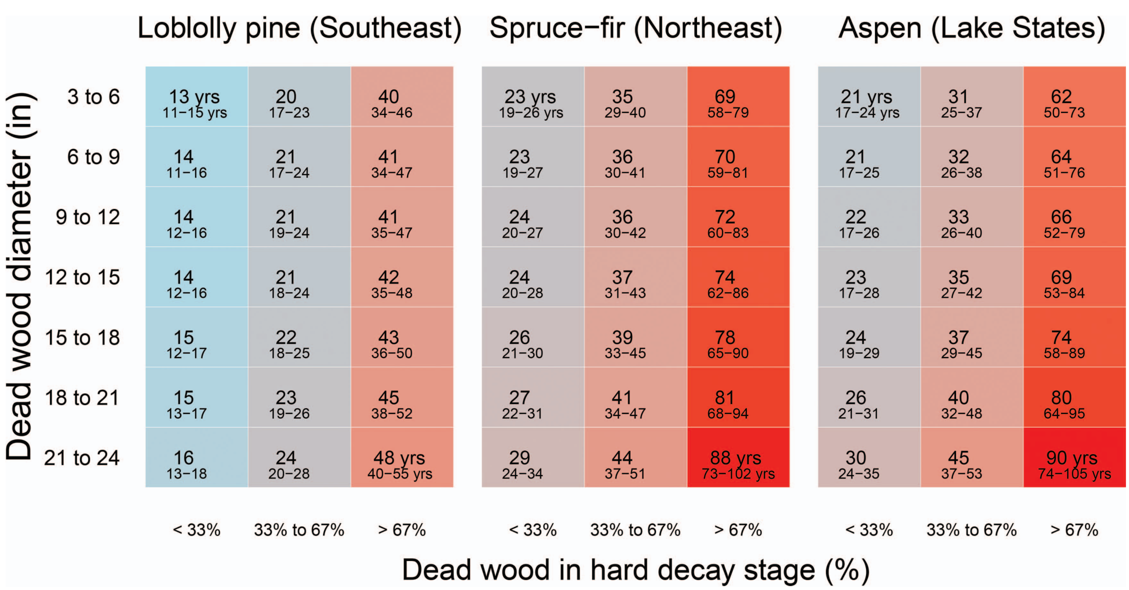


**Figure 2. Deadwood forecasting tools for common forest types in the eastern United States, with values indicating mean residence time of biomass in years (estimates of liberal and conservative residence times appear below means), assuming that average deadwood diameter and percentage of wood in a hard decay stage is known. Warmer and cooler colors indicate longer and shorter residence times, respectively.**

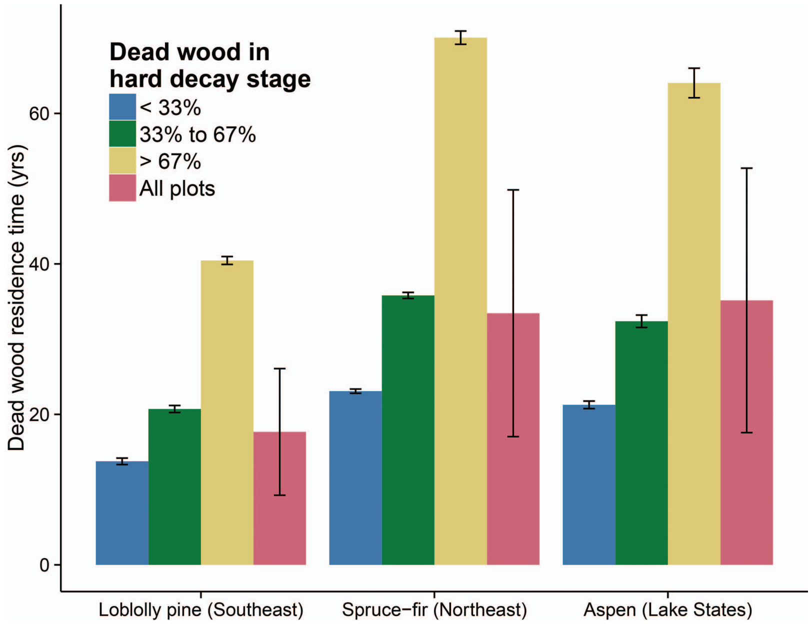


**Figure 3. Mean residence times (±SD) of deadwood biomass using current populations from the FIA down woody materials indicator for common forest types in the eastern United States.**

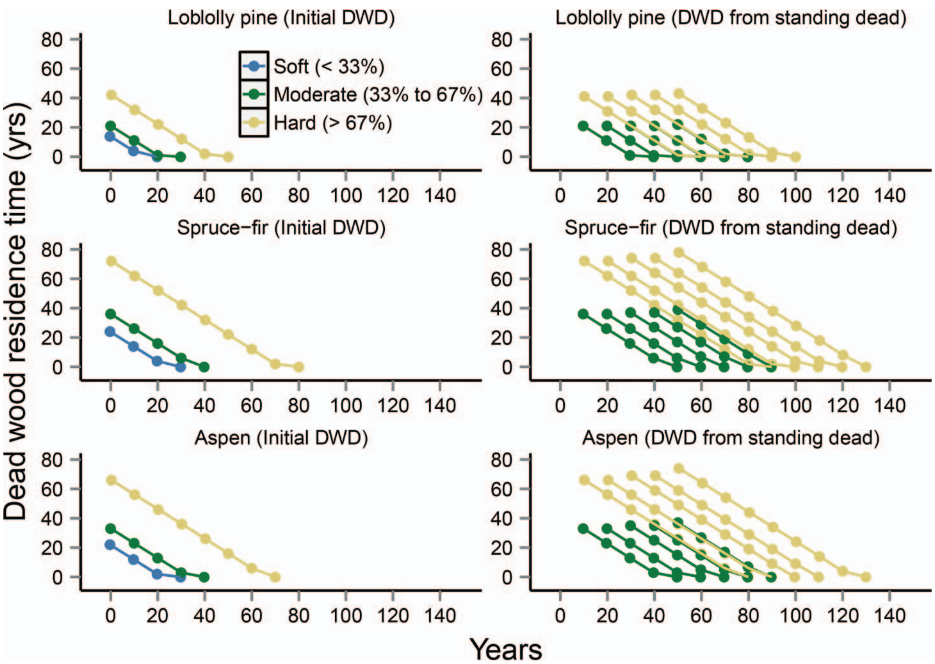


**Figure 4. Trends in DWD residence times assuming decomposition of initial DWD (left) and assuming inputs from standing dead trees for 50 years into the DWD pool (right) for common forest types in the eastern United States.**

et al. 2015), few management tools that provide insight into the temporal dynamics of DWD in forest ecosystems have been created. We propose that quantifying the average diameter of DWD and its general stage of decay and the residence time of deadwood biomass pools can be considered as a part of forest management planning. Such measurements could enhance existing forest inventories to determine current and future DWD stocks that have implications for addressing a number of forest structural features such as biodiversity and wildlife habitat availability.

The emphasis here was primarily on the development of DWD forecasting tools for even-aged and generally single-species forests. From a DWD perspective, these forests may present the least variability in terms of ranges of DWD sizes, stage of decay, and differences in residence times for species inherent to the forest type. At a very coarse level, hardwoods tend to decay more rapidly than conifer species (Weedon et al. 2009), future climate scenarios may lend to more rapid decomposition of DWD depending on region (Russell et al. 2014a), and differences in residence time are apparent, depending on whether wood density, volume, or biomass is of interest (e.g., Fraver et al. 2013). Implementation of such tools for uneven-aged and/or mixed-species stands may be developed and refined with these parameters in mind, in addition to the range in expected variability of DWD biomass. The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE) (Reinhardt and Crookston 2003, Rebain et al. 2010) may present a useful starting point for refining DWD dynamics within a forest growth and yield simulation tool. The FFE modeling framework allows users to specify a mass loss rate of DWD for various size classes and to change rates of standing dead tree height loss and fall rates, all of which serve as direct inputs into the DWD pool. Refinement for mixed-species and uneven-aged forests may focus on augmenting existing forecasting tools such as FFE through implementing species-, size-, and decay stage-specific parameters to better reflect DWD dynamics for a variety of species and stand conditions.

Although we assumed that standing dead tree inputs into the DWD pool would only occur from pieces in moderate to hard decay, given the relatively short longevity of standing dead trees in these forest types (e.g., 6 years in spruce-fir forests; Garber et al. 2005), users could include standing dead trees in soft decay stages based on local knowledge of standing downed wood dynamics. In addition to standing dead trees, other inputs such as freshly fallen live trees (Woodall and Nagel 2007) could be considered in the future development of our proposed tool. The variability surrounding estimates of DWD residence times within the same forest type are probably associated with climate differences across the region, variability in DWD sizes, and past management history. The importance of the forecasting tool relies on quality DWD inventory information; however, additional knowledge about stand conditions and past management activities will aid in refining the tool for application in local forests. This may include knowledge of microclimate conditions that could subsequently affect the decay of deadwood (e.g., Crockatt and Bebber 2014). To improve the accuracy of DWD residence times, emerging information from the P2+ program of FIA will provide more DWD observations from a range of forest types and stand conditions across the northern United States (USDA Forest Service 2014a). Currently being collected on approximately 12.5% of FIA plots, these additional DWD measurements can be used to reduce uncertainty estimates associated with residence times and deadwood dynamics.

Residence times presented in the DWD forecasting tool provide expected rates of decay, depending on the various forest types (e.g., loblolly pine deadwood decomposes at a faster rate than northern forest types such as spruce-fir and aspen) (Figure 3). Residence times presented here align well with values presented by others for loblolly pine (25 years presented by Mobley et al. 2013; 22–35 years presented by Radtke et al. 2009), balsam fir (77–154 years presented by Lambert et al. 1980), and aspen (38 years presented by Alban and Pastor 1993). Measurements of DWD obtained from FIA observations have been useful in the development of the forecasting tool and may continue to be used in the future despite slight changes in DWD measurements collected by FIA. In the emerging P2+ network of FIA plots, DWD may be sampled on up to 25% of all FIA field plots in regions of the United States (USDA Forest Service 2014a), whereas line transects will continue to collect pertinent DWD measurements such as diameter at transect and decay class. These measurements can be collected using relatively rapid assessments in the field, can be summarized to the plot or stand level (as in the case study presented above), and can be implemented within the DWD management framework to determine residence times (i.e., Figure 3). Users concerned with more accurate representations of DWD volume and/or biomass for individual pieces (i.e., not solely basing estimates of DWD volume or biomass on transect diameter alone) could measure both small- and large-end diameters in addition to piece length or turn to equations that estimate these values based on transect diameter and decay class (i.e., Woodall et al. 2008).

## Examples of Applications

The application of a DWD forecasting tool can prove useful in a number of contexts, ranging from assessing fire risk and fuel loads, to evaluating the role of forest structural attributes in providing wildlife habitat, to determining biomass losses from DWD pools in carbon accounting frameworks. With appropriate local knowledge of deadwood residence times for specific stand conditions (which may or may not be informed using FIA data), the forecasting tool may be adapted to suit an individual user's needs (e.g., Supplemental File S1). In forests with complex structures of deadwood (e.g., disparate populations with freshly fallen and highly decayed DWD), the forecasting tool may be used independently within the same forest for delineated populations. Two examples of the potential application of the developed tools to inform management objectives are below.

***Biomass Harvesting and Resulting Deadwood.*** A recent biomass harvest occurred on an aspen-dominated site in Minnesota. Per forest management guidelines that were developed for the region (Minnesota Forest Resources Council 2012), one-third of all tops and limbs were distributed across the site after harvest. In addition, three 14-in. DWD pieces per acre (with bark-on) were created in a nearby riparian area to promote biodiversity and habitat structure. In a postharvest assessment of the site, foresters note that the remaining slash from the biomass harvest is between 3 and 6 in. and in a moderate decay stage (50% of deadwood in a hard decay stage), whereas DWD created in the riparian area is an average of 14 in. in size and is characteristic of hard decay. The foresters conclude that residence time for the slash biomass on site would be around 31 years (range from 25 to 37 years), whereas the larger-diameter DWD in the riparian area would approximate 69 years (range from 53 to 84 years) (Figure 2).

***Forest Structure for Wildlife-Dependent Species.*** A team of wildlife biologists is interested in surveying a spruce-fir forest in northern Maine for suitable habitat for American marten (*Martes americana*), a carnivorous mammal associated with mature forests (Hargis et al. 1999). After conducting line intercept sampling to assess current DWD stocks, the team concludes that average DWD is 9 in. with the majority of pieces displaying moderate decay (50% in a hard decay stage). Although the biologists notice several hollow logs that may be appropriate as resting sites for marten, they have some concern, given the relatively short residence time for existing DWD biomass (36 years [range from 30 to 42 years]) (Figure 2). Hence, future inputs of freshly fallen DWD are a concern in this forest to sustain suitable future marten habitat. The team agrees to conduct another inventory in 10 years to reassess deadwood stocks and inventory new DWD inputs.

## Conclusions

Large-scale multiresource (e.g., growing stock and deadwood) forest inventories may be used to inform forest management beyond basic resource statistics. Ecological relationships identified by inventories, such as DWD residence times by climatic region, may be used to construct forecasting tools to address emerging resource questions. In our study, relationships between DWD diameter and stage of decay provided a framework for determining the longevity of DWD biomass in forests across the eastern United States. Results from this prototypic DWD forecasting diagram suggest that forest types that are found in warm climates (e.g., loblolly pine) will undergo decomposition more rapidly than forests in cooler climates (e.g., spruce-fir and aspen). Although the initial development of this study's diagram used average DWD diameter and the proportion of woody debris in hard versus soft stages of decay as inputs to understand future deadwood biomass pools, future researchers should seek to refine DWD metrics (e.g., optimal metrics of size related to residence time), explore the impact of DWD inputs (e.g., branch fall and/or wind throw), and expand related resource inventories. The guides developed can be used to assess whether or not forest management objectives related to deadwood can be met or whether alternative strategies for proactively managing the presence and abundance of deadwood will be needed. We further suggest that such forecasting tools be developed for additional forest types, additional deadwood pools (e.g., standing dead trees), and additional woody debris attributes such as volume. As interest regarding the utilization of forest biomass continues to increase, we expect a concomitant focus on the longevity of DWD in relation to a forest's ecosystem services (e.g., carbon balance) with a need for management information.

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