RESEARCH ARTICLE

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Silviculture

Assessing Tree Mortality Probability in Harvested Hardwood Stands Using Long-Term Forest Inventory Data

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Partial harvesting (here defined as removal of ≤50% of preharvest volume) is the predominant silvicultural scheme applied to hardwood forest types in the eastern United States. Future stand conditions are largely reliant on trees retained after harvest, so their mortality because of harvesting activity damage should be minimized or taken into account when planning. We quantify partially harvested stand characteristics and postharvest mortality using data from 32,057 forested conditions, 366,953 trees with a diameter at breast height (dbh) ≥ 2.5 cm, of which 4,469 trees were cut and used in partially harvested stands. On average 23.3% of stand volume was selectively harvested with an additional 2.5% of volume lost to harvesting-caused mortality. Of the trees killed by logging activity in harvested stands, 90.7% were under 28 cm dbh. The likelihood of mortality was 1.31 times higher (95% CI of 1.20 to 1.44) for trees retained in stands that had undergone partial harvesting than for trees growing in unharvested stands. Commercial species had lower odds of mortality (0.88 times) in harvested stands than noncommercial species. Residual trees in harvested stands on private lands had a higher probability of mortality (1.23 times) than those on harvested public lands.

Study Implications: The loss of an appreciable percentage of retained tree volume because of damage caused by partial harvesting in eastern US hardwood forests reduces stand management options and future value, not only by directly killing trees and affecting advance regeneration but also by reducing the quality of the retained trees for wood products if they are damaged by logging activities. These losses could potentially be minimized through logger education and certification, increasing the prevalence of management plan preparation and timber sale monitoring by professional foresters, and increasing landowner awareness of the importance of protecting the health and value of retained trees.

Keywords: selective harvesting, tree damage, silviculture, logistic regression, residual tree mortality

Partial harvesting is the predominant method of timber extraction used in hardwood-dominated forests of the eastern United States (Brandeis 2017, Luppold and Bumgardner 2018). Silvicultural systems applied in this region commonly strive to maintain the sustainable harvest of wood products and continued delivery of forest ecosystem services in part by ensuring adequate natural regeneration of desired tree species. These silvicultural systems can take a variety of forms according to forest conditions, management goals, forest policies, and land management regulations. Examples include seed-tree, shelterwood, and a wide variety of schemes under the broad category of uneven-aged management (Smith et al. 1997). Commercial and precommercial thinnings are also applied to stands, as well as timber stand improvement interventions, to concentrate growth on desirable crop trees. These silvicultural systems all use the selective harvesting of trees to put the stand on track to maintain or increase the ability to deliver desired products and ecosystem services. Future stand conditions are largely reliant on trees retained after harvest so ensuring the survival of good quality trees can be essential to meeting long-term management goals.

Felling mature trees may damage or kill residual trees, however, especially the smaller, younger trees in the understory, which are the advance regeneration in stands under uneven-aged management. Skidding the felled trees out of the forest can damage residual tree butt logs and break off or bend over smaller trees. Roots can also be damaged by skidder activity, particularly in saturated soils. Logging

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wounds are potential infection sites of fungi and insects that can cause wood decay and possibly death (Shigo 1966). Meadows (1993) observed that 62% of residual trees were damaged in partial cutting (thinning) of bottomland hardwoods, mostly skidder damage on the lower bole and exposed lateral roots. Most of the destroyed trees were less than 12.7 cm (5 inches) in diameter and in the lower crown classes (Meadows 1993). Skidder-caused damage was also prevalent in a northern hardwoods thinning study (Erdmann et al. 1986). Lamson et al. (1984) observed that 22–45% of residual trees in a partially harvested stand were destroyed or severely bent, with the percent damage increasing with increasing retention basal areas which ranged from 45% to 75% residual stocking. Clatterbuck (2006) also observed increasing percentages of damaged residual trees with increasing residual basal area retention levels in partially harvested (50%, 25%, and 12.5% basal area retention) hardwood stands in Tennessee. More than 76% of residual trees were damaged regardless of the retention level, with 45% of the trees suffering sufficiently severe damage to decrease the future value of the trees by decreasing the log grade by at least one class. Most of the damage was caused by logs scraping against residual trees during skidding. Between 11% and 16% of residual trees were destroyed during logging (Clatterbuck 2006).

Nyland (1989), P. 8-02-1 makes a general statement based on accumulated observations that up to one-fifth of the residual basal area may suffer major injuries (defined as "broken branches larger than 7.6 cm (3 inches) diameter or wounds exposing more than one-third of the bole circumference") to the crown or main stem in partially cut uneven-aged stands. Additionally, reentry in subsequent cutting to further develop uneven-aged stand structure would have a cumulative effect of injuring new trees and reinjuring those damaged in the previous cutting cycle which may force a reassessment of management objectives (Nyland 1989). When even-aged stand structures that rely on natural regeneration are the management goal, overstory tree felling damages the future crop trees. Again, based on observations, Nyland (1989) states that damage caused by thinning could result in an additional loss of residual relative basal area of 10%, with 20% of the residual trees damaged by skidding.

As the above brief literature review shows, there have been studies quantifying the numbers of damaged and destroyed trees in partially harvested hardwood stands. The authors of these studies frequently express concern about the potential for future mortality of the more severely damaged residual trees. However, none of these studies covered a sufficiently long period of time to quantify postharvesting mortality. The USDA Forest Service's Forest Inventory and Analysis (FIA) program, the national forest inventory of the United States, collects data on the forest status and health across all the United States, associated commonwealths, and territories. Although first established in 1928 by congressional mandate, renovations to the program made in the mid-1990s established a nationwide network of permanent forest inventory and monitoring plots at a base sampling intensity of one plot every 2,428 hectares (6,000 acres) that are remeasured at regular intervals under nationally consistent field data collection protocols. In the eastern United States, this remeasurement interval is every five to seven years, which means there are forest inventory data for hardwood-dominated forests in the eastern United States covering a 20+ year period for most of the eastern United States.

The objectives of our study were to quantify the numbers of trees and wood volume removed and used from hardwood-dominated, partially harvested stands in the eastern United States relative to preharvest volumes. We also wanted to quantify the numbers of trees and amount of wood volume destroyed by these partial harvesting activities. We also wanted to know if trees retained in partially harvested stands had a greater probability of mortality compared with trees in unharvested stands, and if that probability was influenced by whether the tree species was one of commercial value, the tree's diameter at breast height (dbh), if the harvested land was privately or publicly owned, and postharvest stand volume.

Methods

Study Area

We queried FIA's publicly available data Oracle relational database (FIADB) in May of 2019 to extract annualized tree inventory data for timberland, which excludes lands on which harvesting is legislatively restricted and includes only site classes considered to have the potential for timber production (site classes 1–6, which range from 1.4 to 15.5 and above m^3/ha/yr or 20 to 225 and above ft^3/ac/yr) and excluding all standing dead trees. The study area was defined by FIA survey units, broad, multicounty groupings of counties that share physiographic similarities within a state. Typically, a state in the eastern United States will consist of three to seven survey units (Figure 1a).

In terms of Level III Ecoregions of the Continental United States, this study area primarily falls within the Interior Plateau, Western Allegheny Plateau, Central Appalachians, Ridge and Valley, Blue Ridge, and Northern Piedmont ecoregions (US Environmental Protection Agency 2013) (Figure 1b). This area also corresponds to the core area of what is often referred to as the Central Hardwoods region (see Fralish 2003 for detailed delineations). The study area, however, excludes the western portion of the Central Hardwoods region beyond the Mississippi River because we felt it too removed from the main study area, the Appalachian and Allegheny Mountains and their nearby plateau and piedmont areas. The study area also does not extend into the northern portions of Illinois and Indiana where there is more agricultural land than forest land.

Although information on harvesting systems used at each harvest site in the sample is not available, literature on the subject indicates feller-buncher and skidder systems as the predominant systems used across the region (Barrett et al. 2017, Conrad et al. 2018). However, Barrett et al. (2017) also report use of chainsaw felling on Virginia's mountainous terrain, and LeDoux (2011) indicates nonmechanized systems (chain felling and animal or small tractor use for skidding) taking a minor role across harvesting systems used in northern hardwood forests.

Data Queried from the FIA Database (FIADB)

All tree records except those of standing dead trees were extracted from the FIADB. We began by extracting data for all trees in all forest types regardless of whether harvesting occurred, then progressively refined the data set to focus on particular questions of interest. The first reduction was to focus on only hardwood forest types. We will be referring to the areas sampled by the FIA program at each sampling point using the term "condition" rather than "plot." This is because a forested FIA plot may be subdivided into multiple conditions based on whether portions of the plot area is not forested, and changes in forest type, ownership, stand structure, stand age, treatments, disturbances, and other characteristics found within the forested portions. Details on FIA condition mapping can be found in the southern regional USDA field guide, USDA Forest Service 2016.

For those trees that were measured multiple times, each tree record consisted of its time 1 measurements and volume estimates merged with the next remeasurement cycle data, time 2. The FIA program remeasures its plots in the eastern United States on five- to seven-year intervals, but these intervals can change from state to state and from year to year depending on program funding. This complication is unavoidable so one must assume, as does the FIA program when calculating growth, removals, and mortality, that this variance in remeasurement period does not have an appreciable impact on estimates. Individual tree cubic meter volumes were estimated at times 1 and 2 using the National Information Management System (NIMS) formulas and calculations described in Woodall et al. (2011) and Oswalt and Conner (2011). Individual tree volumes were then expanded to what they represent in terms of stand cubic meter volume per acre using the appropriate tree expansion factors (as outlined in Burrill et al. 2018). Additionally, trees were assigned an indicator variable for commercial versus noncommercial species using the FIA tree species group codes (Burrill et al. 2018). Essentially, all species in the FIA "eastern noncommercial hardwoods" species group were considered as noncommercial for this study. We also created a public versus private land indicator variable to test whether there were differences based on land ownership.

When the FIA program estimates the volume of trees that died or were harvested and are therefore unavailable to taking an actual measurement at time 2, the time 1 tree volume is modeled to the midpoint between the two measurements (Pugh et al. 2018). For the southern states used in this study (Alabama, Georgia, Kentucky, North Carolina, Tennessee, and Virginia), past species-level growth rates were used to develop annual increment rates and those applied to estimate midpoint diameters. For northern states used in this study (Illinois, Indiana, Maryland, Ohio, Pennsylvania, and West Virginia), growth models developed by species were used to model midpoint diameters. For survivor trees, midpoint volumes are not normally modeled in NIMS. We calculated them by averaging the time 1 and time 2 volumes. For ingrowth trees which grew from a dbh < 12.7 cm at time 1 (therefore no volume calculated) to a dbh ≥ 12.7 cm at time 2 (when a volume is calculated), the time 2 volume was used as the midpoint volume. This is an unavoidable compromise that we feel will not appreciably overestimate midpoint condition-level volume estimates. Once midpoint volumes were estimated for all trees, they were summed at the condition level. By using midpoint volumes, we were able to compare what proportion of the stand's volume was harvested at the time of harvest rather than later when the plot was remeasured.

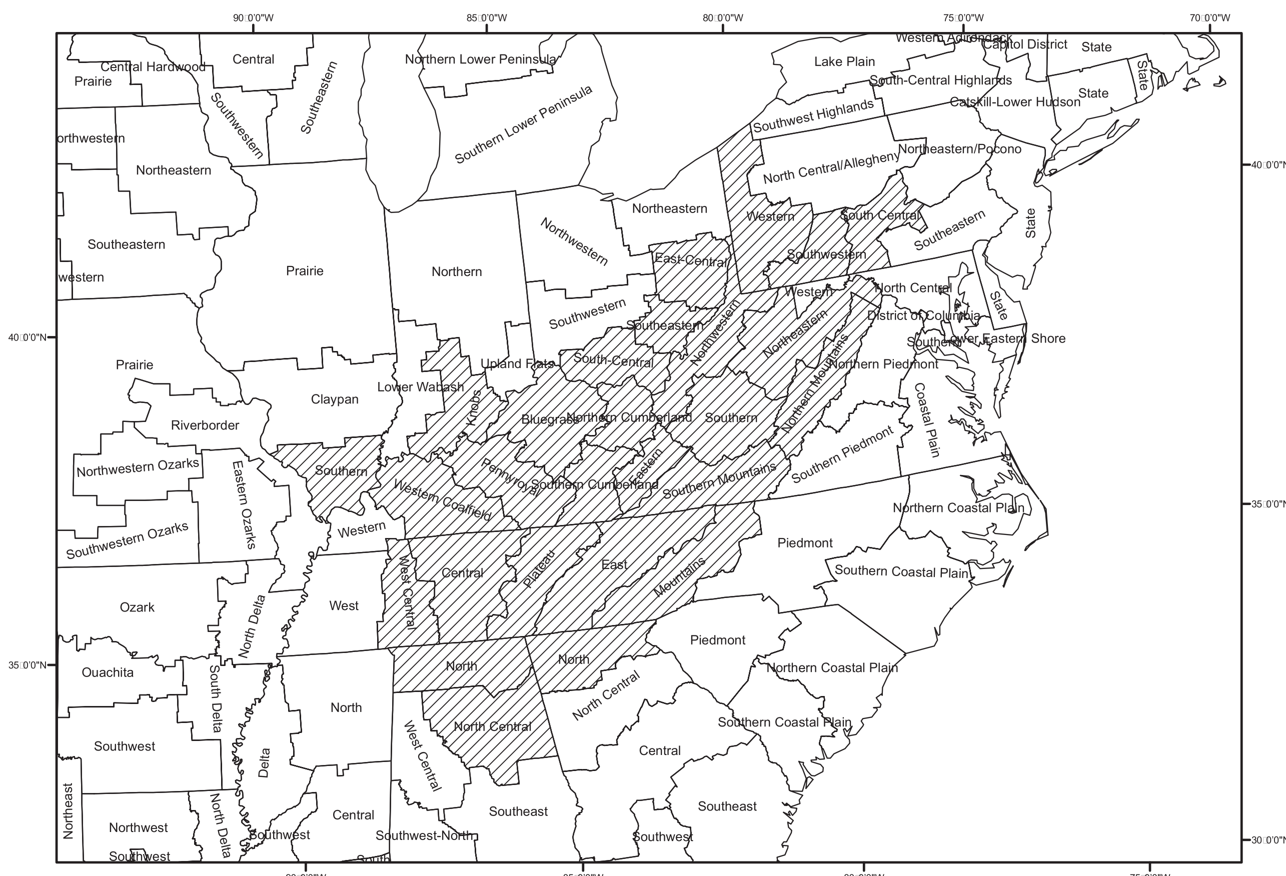

Figure 1. Study area by USDA Forest Service Forest Inventory and Analysis survey units in Alabama (North Central and North survey units), Georgia (Northern survey unit), Illinois (Southern survey unit), Indiana (Knobs survey unit), Kentucky (Eastern, Northern Cumberland, Southern Cumberland, Bluegrass, Pennyroyal, and Western Coalfield survey units), Maryland (Western survey unit), North Carolina

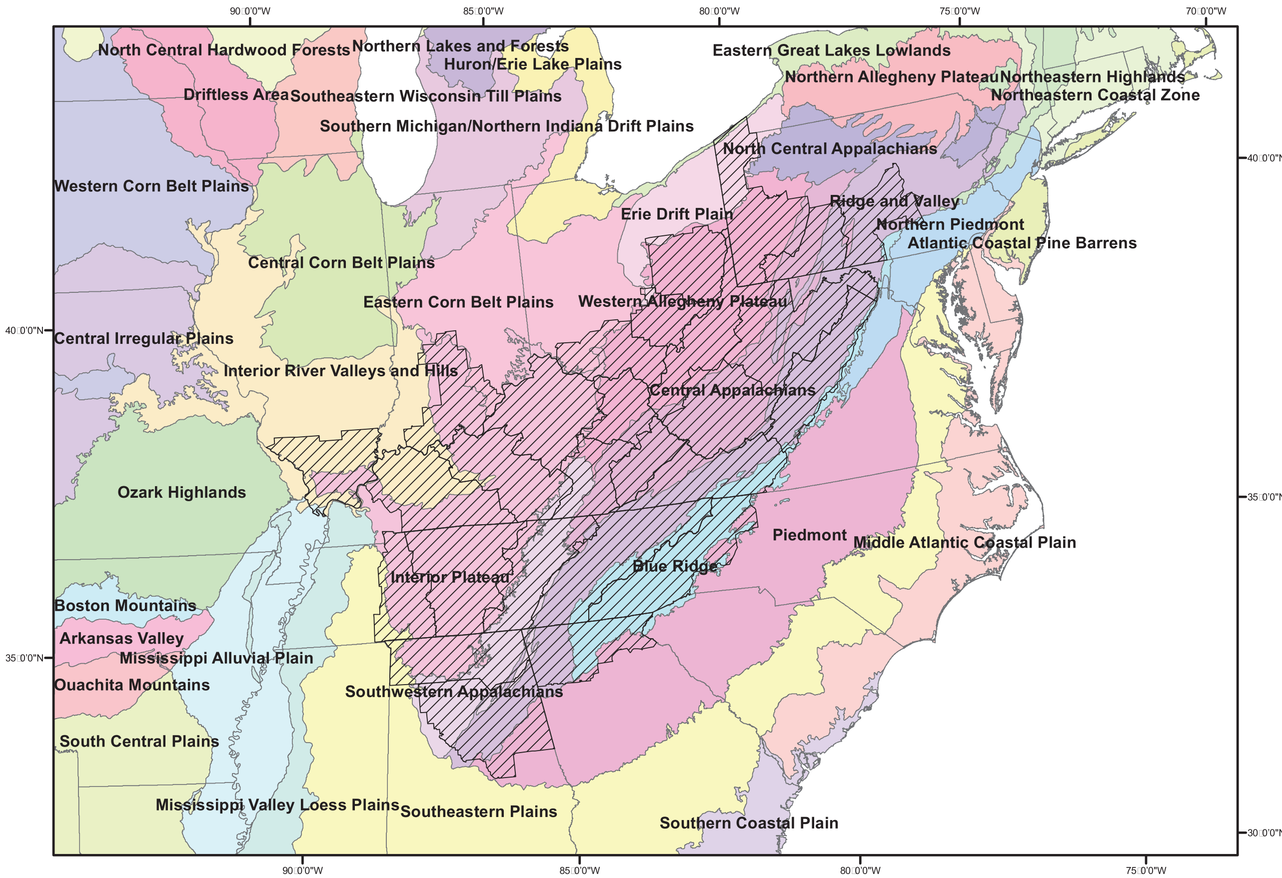

Figure 1. (Continued) **(Mountains survey unit), Ohio (South-Central, Southeastern, and East-Central survey units), Pennsylvania (South Central, Western, and Southwestern survey units), Tennessee (West Central, Central, Plateau, and East survey units), Virginia (Northern Mountains and Southern Mountains survey units), and West Virginia (Northeastern, Southern, and Northwestern survey units) (a) and US Level III Ecoregions (b).**

Table 1. Numbers of forested conditions and individual trees and percentages of totals by state, hardwood forest types only.

State	Conditions		Trees	
	Number	Percent	Number	Percent
Alabama	2,924	9.12	31,298	8.53
Georgia	1,868	5.83	21,024	5.73
Illinois	597	1.86	6,906	1.88
Indiana	1,105	3.45	10,008	2.73
Kentucky	5,544	17.29	61,318	16.71
Maryland	120	0.37	1,880	0.51
North Carolina	1,881	5.87	23,895	6.51
Ohio	1,961	6.12	24,069	6.56
Pennsylvania	2,455	7.66	29,537	8.05
Tennessee	7,269	22.68	73,751	20.1
Virginia	3,220	10.04	34,005	9.27
West Virginia	3,113	9.71	49,262	13.42
Total	32,057	100	366,953	100

Next, we used the information on the causes of individual tree mortality collected by the inventory to separate trees that were cut and used from those that were killed during or after harvesting occurred within the condition. Unfortunately, the data set does not differentiate between those trees killed when harvesting occurred, for example crushed by a skidder, and those trees which died a few years later because of extensive damage. We only know that the trees died between one measurement period and the next, and that the cause of death was due to human activity. Conversely, trees in partially harvested stands killed by other causes, for example a lightning strike or insect attack, would not be included as killed because of harvesting activities. This allowed for the calculation of percent of stand volume per acre harvested and used and percent of stand volume per acre killed during harvest activities but not used.

We were particularly interested in assessing postharvest mortality in partially harvested stands as opposed to mortality in unharvested stands. For data collected in the southern states, a regional cutting codes exists that further categorizes harvesting activity into clearcut harvests, partial harvest, seed-tree/shelterwood harvest, commercial thinning, timber stand improvement, and salvage or sanitation cutting (see southern regional USDA field guide, USDA Forest Service [2016], for more details on these categories). These regional cutting descriptions were not used in the northern states, so the occurrence of partial harvesting had to be assumed based on the percentage of stand volume removed. Partial harvests in Tennessee and Kentucky, where the cutting categories were recorded, removed on average 47.4% of the stand volume (Brandeis 2017). The southern regional cutting category for clearcut harvests was defined as "the removal of the majority of the merchantable trees in a stand; residual stand stocking is less than 50%" (USDA Forest Service [2016], this quoted text comes from section 2.5.43, P. 65). Based on this, we chose to define partial harvesting as the removal of 50% or less of the stand's time 1 volume. This means that partial harvesting as used in this study included shelterwood and seed tree cuts, commercial

Table 2. Numbers and percentages of live trees, harvested trees, and killed trees by diameter class (centimeters) in hardwood forest types.

Diameter-at-Breast-Height Class	Total Trees		Harvested Trees		Killed Trees	
	Number	Percent	Number	Percent	Number	Percent
2.5–7.5	54,870	15.0	142	0.8	1,988	39.4
7.6–12.6	15,381	4.2	142	0.8	495	9.8
12.7–17.7	108,988	29.7	4,238	24.7	1,470	29.2
17.8–22.8	63,331	17.3	3,353	19.5	575	11.4
22.9–27.8	42,286	11.5	2,389	13.9	230	4.6
27.9–32.9	29,129	7.9	1,807	10.5	137	2.7
33.0–38.0	20,445	5.6	1,540	9.0	65	1.3
38.1–43.1	13,378	3.7	1,387	8.1	27	0.5
43.2–48.2	8,126	2.2	923	5.4	22	0.4
48.3–53.2	4,750	1.3	583	3.4	14	0.3
53.3–73.6	5,615	1.5	616	3.6	15	0.3
73.7+	654	0.2	41	0.2	4	0.1
Total	366,953	100.0	17,161	100.0	5,042	100.0

Table 3. Frequency of tree remeasurement by state, hardwood forest types only.

State	Number of Remeasurements				
	1	2	3	4	Total
Alabama	15,217	7,687	8,394	-	31,298
Georgia	10,391	3,979	3,956	2,698	21,024
Illinois	3,365	3,146	395	-	6,906
Indiana	4,429	3,870	1,709	-	10,008
Kentucky	22,828	29,060	9,430	-	61,318
Maryland	918	962	-	-	1,880
North Carolina	8,427	10,044	5,424	-	23,895
Ohio	9,690	13,515	864	-	24,069
Pennsylvania	10,888	11,827	6,822	-	29,537
Tennessee	29,605	17,829	19,640	6,677	73,751
Virginia	9,441	10,118	12,251	2,195	34,005
West Virginia	26,686	22,576	-	-	49,262
Total	151,885	134,613	68,885	11,570	366,953
Percent total	41.4	36.7	18.8	3.2	100.0

thinnings, timber stand improvements, and salvage or sanitation cuts. In Tennessee and Kentucky, these silvicultural treatments accounted for only a small portion of the harvest removals, so we chose to include them in the broader partial harvest category here (Brandeis 2017). We felt this was valid as postharvest mortality would be relevant under these treatments as well.

Logistic Regression

Conditions were assigned a binary code indicating partial harvesting (harvest = 1 if partial harvesting had occurred, and harvest = 0 otherwise). This code was assigned to the condition from the first occurrence of harvesting and to all future remeasurement of that condition, regardless of whether harvesting occurred again. This was done to capture delayed mortality (e.g., a tree that is badly damaged but takes more than the five- to seven-year remeasurement interval to die).

Descriptive harvesting statistics were calculated with Statistical Analysis System (SAS ver. 9.3) (SAS Institute, Inc., 2011). Logistic regressions were performed in STATA (ver. 15.1) initially using the mixed modeling procedure ("melogit" command) and later logistic regression ("logit" command), specifying that the response variable had a binary distribution (=1 if the tree was dead and =0 otherwise). Condition was initially treated as a random effect to account for nesting of trees within conditions and therefore their lack of independence, and the random errors were specified with a normal distribution because of the large numbers of conditions (Dai et al. 2006). Preliminary modeling indicated that it was not necessary to treat condition as a random effect because the residual interclass correlation statistics showed that trees within conditions were not highly correlated (0.127, or 12.7%). In the final models, we used logistic regression robust standard errors which were adjusted for the clustering of trees at the condition level.

$$logit\left(\pi_{ij}\right) = \alpha + + \beta x_{ij} + u_{ij} \qquad (1)$$

where π is the probability of a tree i being dead on condition j, conditional on the vector of explanatory variable x; intercept α, β represents parameter estimates; and u represents the random error term.

Explanatory variables included in the preliminary models were whether the condition was partially harvested at some point during the study period; whether the tree species was a commercial one; ownership (public versus private); tree dbh, specified as a categorical size class (trees with dbh ≥ 12.7 cm and saplings <12.7 cm) and also evaluated as a continuous variable; and time 2 stand volume as a surrogate for postharvest stand density (hypothesizing that greater residual stand density might make avoiding residual tree damage more difficult and increase tree mortality). Model classification was evaluated using the area under the receiver operating characteristics curve (AUROC).

Results

Harvested Stand Characteristics

Between the years of 1998 and 2018, on forested conditions which fell within hardwood-dominated forest type groups, the FIADB query produced 674,046 observations on 366,953 individual trees on 32,057 forested conditions (Table 1). The states with the most trees sampled were Tennessee (20.1% of the total) and Kentucky (16.7%), of which 77.6% had dbh < 28 cm (11.0 inches, the minimum diameter for a hardwood tree to be considered sawtimber-size by FIA) (Table 2). The trees with dbh < 12.7 cm (5 inches) at time 1 were ingrowth trees that grew to dbh ≥ 12.7 cm at time 2. More than 40% of the trees were only measured one time (41.4%) and only a small percentage (3.2%) were measured up to four times (Table 3).

During the study period in hardwood forest types, mean percent time 1 stand volume harvested by all harvesting types, including clearcutting, was 46.1% (Figure 2). A total of 17,161 trees were harvested from the above sample (Table 2). An additional 2.5%

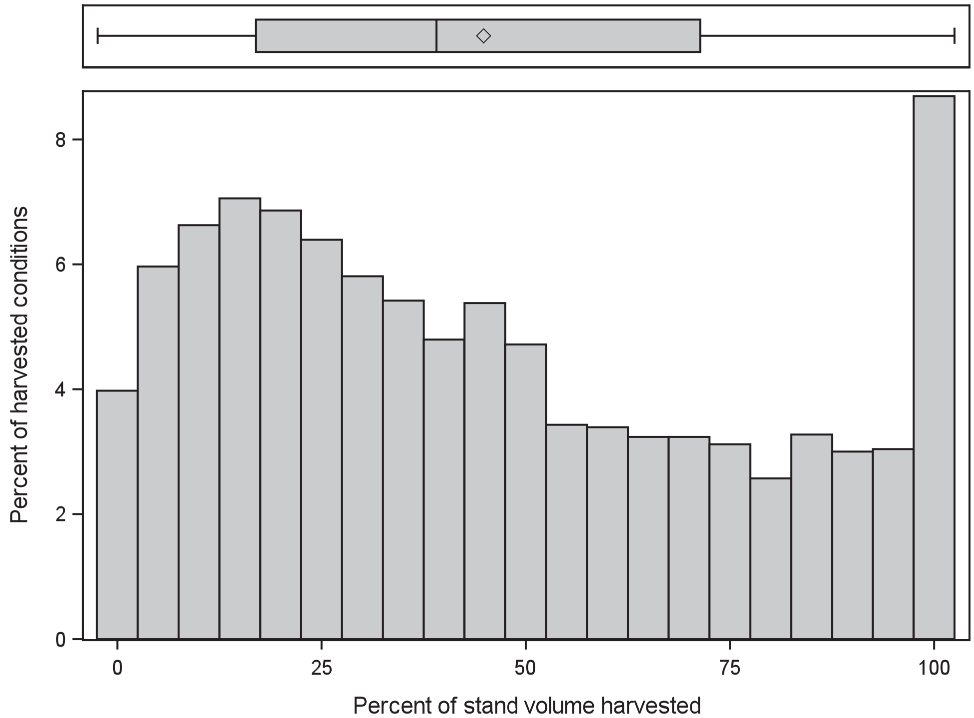

Figure 2. The percent of remeasured Forest Inventory and Analysis plot conditions with harvesting activity of all types (including clearcutting) by the percent of time 1 volume harvested from those conditions. The box and whisker plot indicates median (vertical line) and mean (diamond) values.

Table 4. Numbers and percentages of harvested and killed trees by diameter class (centimeter) in hardwood forest types.

Diameter-at-Breast-Height Class	Harvested Trees		Killed Trees	
	Number	Percent	Number	Percent
2.5–7.5	45	1.0	678	31.2
7.6–12.6	24	0.5	176	8.1
12.7–17.7	851	19.0	713	32.8
17.8–22.8	566	12.7	282	13.0
22.9–27.8	475	10.6	121	5.6
27.9–32.9	518	11.6	92	4.2
33.0–38.0	539	12.1	51	2.4
38.1–43.1	599	13.4	17	0.8
43.2–48.2	380	8.5	17	0.8
48.3–53.2	228	5.1	10	0.5
53.3–73.6	231	5.2	10	0.5
73.7+	13	0.3	4	0.2
Total	4,469	100.0	2,171	100.0

of volume was killed but not used consisting of 5,042 trees (2,483 trees with dbh ≥ 12.7 cm) (Table 2).

When we set the 50% limit for partially harvested stands, the mean stand volume removed was 23.3% from 4,469 trees (69 trees with dbh ≥ 12.7 cm; Table 4, Figure 3) with an additional 2.5% again being killed but not used from 2,171 trees (854 trees with dbh ≥ 12.7cm; Table 4, Figure 4) recorded from 1,457 forested conditions. In these partially harvested stands, 92.8% of postharvest mortality trees were under 30 cm dbh, and 53.5% were between 12.7 and 29.9 cm dbh.

Likelihood of Postharvest Mortality

Models that included a variable indicating whether the tree was less than 12.7 cm dbh (sapling versus tree) and the time 2 volume did not show statistical significance for either variable. Therefore, the final model included indicator variables for partial harvest, commercial species, and private ownership, as well as tree dbh as a continuous variable. The model also included interaction terms between partial harvest and commercial species, and partial harvest and private ownership. The model's AUROC was close to 65%, indicating marginal prediction.

All interaction terms where statistically significant (Table 5). We see from Table 5, that larger trees (increasing dbh) have decreasing odds of mortality (0.988 times). Because of the interaction terms, odds ratio interpretation for other variables is not as direct, and we turn instead to predictive margins. Predictive margins present the probability of tree mortality for each level of the interacted variables and at various levels of dbh. The predictive margins showing the probability of mortality in partially harvested and unharvested stands of commercial and noncommercial species versus dbh with 95% confidence intervals appear in Figure 5.

Noncommercial tree species on harvested stands had a higher probability of mortality than commercial tree species in harvest stands and that difference was higher in small size trees. As the tree dbh increases, mortality probability across commercial and noncommercial trees converge and decrease (Figure 5). Residual trees in harvested stands on private lands had a higher mortality probability than those on harvested public lands. With increasing tree dbh, mortality probability decreased across all ownerships (Figure 6).

Discussion

Our results confirm and quantify the smaller-scale observations of previous researchers, that partial stand harvesting in eastern US hardwood-dominated forests typically experience an appreciable amount of harvest-induced mortality. The loss of volume because

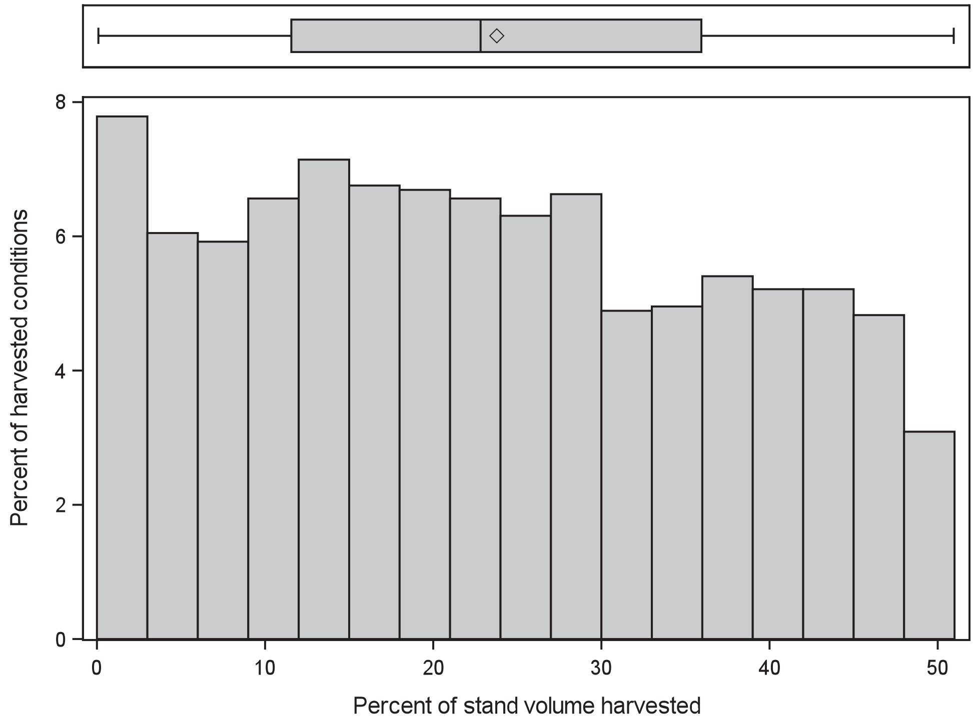

Figure 3. The percent of remeasured Forest Inventory and Analysis plot conditions with partial harvesting activity (50% or less of the volume harvested) by the percent of time 1 volume harvested. The box and whisker plot indicates median (vertical line) and mean (diamond) values.

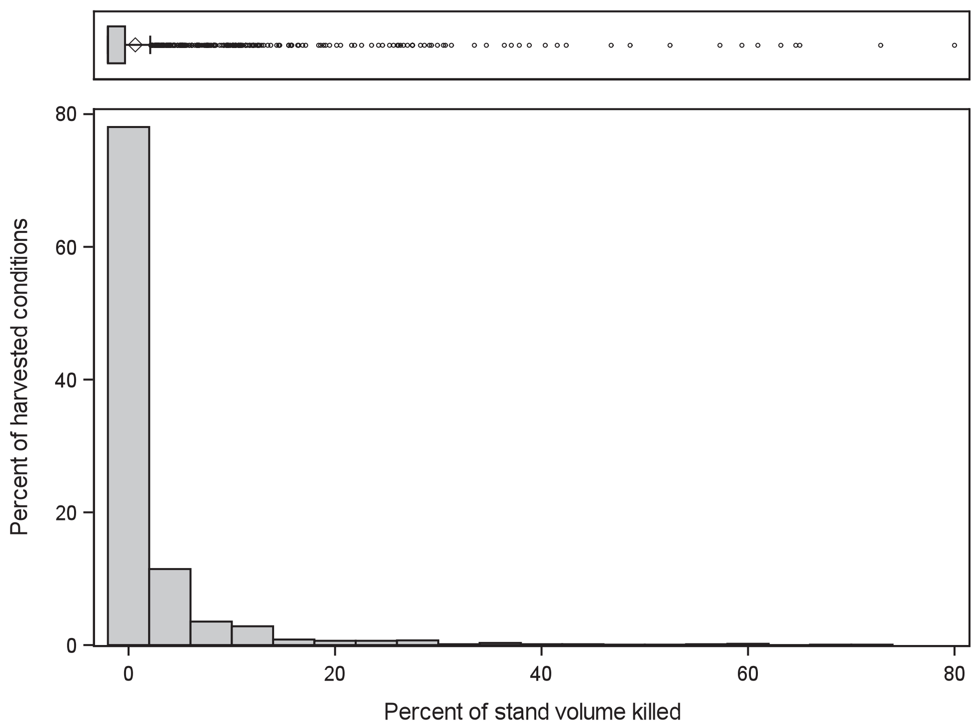

Figure 4. The percent of remeasured Forest Inventory and Analysis plot conditions with partial harvesting activity (50% or less of the volume harvested) by the percent of time 1 volume killed. The box and whisker plot indicates median (vertical line) and mean (diamond) values.

of mortality observed (2.5% of the initial stand volume) was less than would have been expected based on previous observations of the percent of retention trees damaged (ranging from roughly 25–75% of the trees) which would indicate these damages do not always result in eventual tree death. One percent to 7% of the residual basal area was destroyed by harvesting activities in commercially thinned hardwood forests in Michigan (Bruhn 1986). The destroyed trees were less than 20 cm in dbh.

Table 5. **Logistic regression odds ratios and test statistics for mortality within selectively harvested stands (Harvest), for commercial and noncommercial tree species (Commercial) and private or public landownership (Private ownership), with diameter at breast height (dbh) as a continuous variable.**

Variable	Odds Ratio	Robust Standard Error	*z*	*p* > |*z*|	95% Confidence Interval	
					Lower	Upper
Intercept	0.2692006	0.0063142	–55.95	0	0.2571051	0.2818652
Harvest	1.312858	0.0600429	5.95	0	1.200296	1.435975
Commercial spp.	0.8222191	0.0182793	–8.8	0	0.7871616	0.8588379
Harvest × Commercial	0.8858774	0.0413354	–2.6	0.009	0.8084556	0.9707135
Private ownership	0.9436937	0.0201697	–2.71	0.007	0.9049784	0.9840652
Harvest × Private	1.229794	0.1055704	2.41	0.016	1.03935	1.455133
dbh	0.899109	0.0017203	–55.58	0	0.8957436	0.902487
Log pseudolikelihood = –177,400.81						

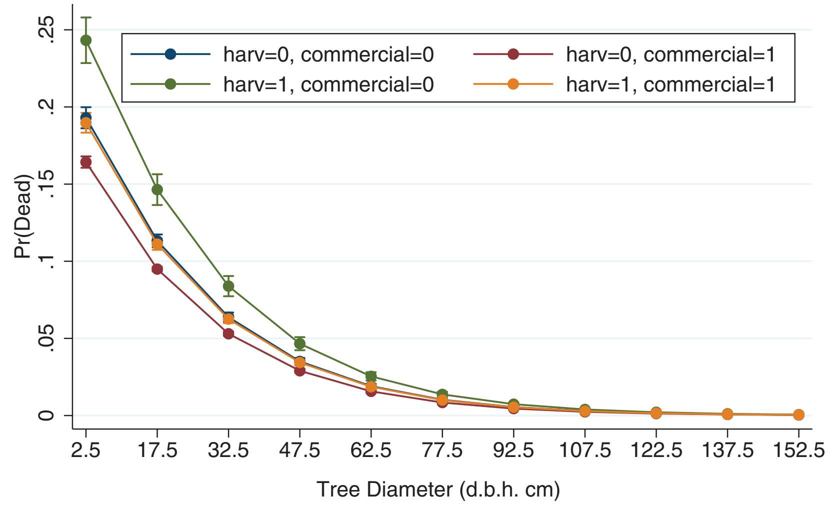

Figure 5. The predictive margins showing the probability of mortality in partially harvested and unharvested commercial and noncommercial species versus diameter at breast height (dbh) with 95% confidence intervals.

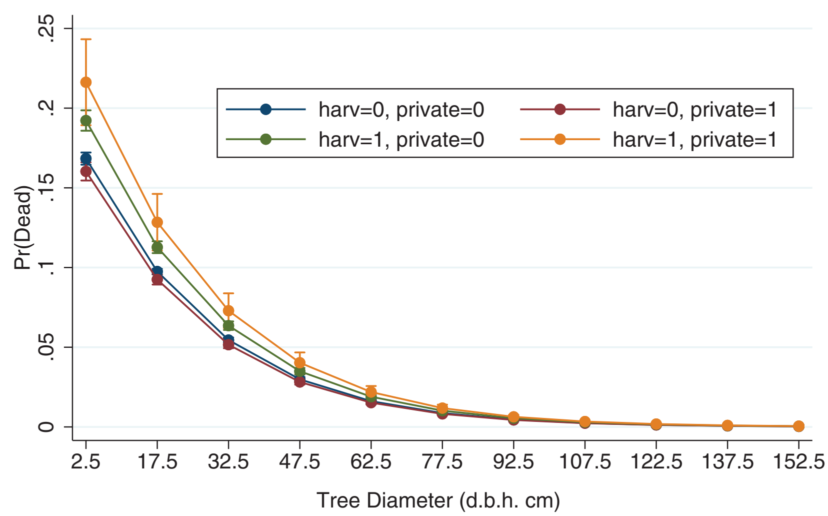

Figure 6. The predictive margins showing the probability of mortality in partially harvested and unharvested private and public land versus diameter at breast height (dbh) with 95% confidence intervals.

It is notable that the probability of tree mortality was higher on privately owned land than on public land. This might imply greater care being taken by the loggers on public land to not damage the residual trees, perhaps because of contract requirements, and closer supervision by public land managers. The lowered mortality in commercial trees might indicate greater care being taken to protect those future crop trees and more willingness to accept damage to less valuable noncommercial species.

In any case, these numbers of damaged trees would certainly lower the quality of the stems for use as wood products in the retained stand. Although reducing the residual stand basal area will make additional resources available to the residual trees, there is the possibility of damage during logging which may reduce the value of that tree or even kill it. Brandeis (2017) observed that in the states of Kentucky and Tennessee there was some indication of a trend toward there being a lower percentage of total volume in the higher quality tree grades and higher percentages in lower grades. Silviculturalists must also consider that residual tree damage and mortality reduces the selection of future crop trees, thus limiting their options for management.

The degree of residual tree damage seems highly variable and, based on anecdotal mentions by previous study authors, dependent on the skills of the loggers conducting the harvest and the equipment available to them. Increasing levels of basal area retention increase the probability of logging damage to the residual trees because the increased density makes it hard for fellers to avoid felling one tree on top of another and it makes it harder for skidders and mechanical harvesting equipment to maneuver (Bruhn 1986). Smaller, more maneuverable equipment, purposely leaving some "bump" trees to act as pivot points along skid trails, careful marking of crop tree, and increasing the skill of equipment operators were cited as ways of potentially reducing logging damage (Bruhn 1986, Erdmann et al. 1986). Studies from the northern United States also recommend avoiding harvesting in the spring and early summer when trees are actively growing and their bark is "looser," making them more susceptible to surface damage. Frozen soils can also help protect trees from root damage, as can the use of corduroy/slash matting in the southern United States where growing seasons are longer and soils may not freeze at all in the winter.

Perhaps some lessons can be applied to the partial harvesting of hardwood stands in the eastern United States that have been learned in the harvesting of tropical forests. Reduced impact logging (RIL) has among its goals to reduce felling damage to future crop trees where the harvesting of few, highly valuable trees can cause considerable damage to the remaining ones. Examples from logging operations in the Brazilian Amazonia Pará forests have shown a 50% reduction in residual trees killed by felling and a 90% reduction in soil disturbance (Lentini et al. 2010). Holmes's (2016) review of side-by-side comparisons of conventional logging (CL) and RIL shows in almost all cases that despite initially higher costs and lowered income, in the long-term with future harvest entries, RIL harvesting operations generated comparable or superior economic returns. Although these additional efforts to protect residual trees may require more time and effort, and therefore more investment initially, in the long term silviculturalists will have healthier stands and more options for management, and landowners might see greater long-term economic returns.

Literature Cited

Barrett, S.M., C.M. Bolding, and J.F. Munsell. 2017. Characteristics of logging businesses across Virginia's diverse physiographic regions. *Forests* 8(12):468.

Brandeis, T.J. 2017. *Partial harvesting of hardwood sawtimber in Kentucky and Tennessee, 2002–2014.* USDA Forest Service e-Gen. Tech. Rep. SRS–227, Southern Research Station, Asheville, NC. 10 p.

Bruhn, J.N. 1986. Damage to the residual stand resulting from mechanized thinning of northern hardwoods. P. 74–84 in *Hardwood thinning opportunities in the Lake States: Proceedings of a symposium*, Sturos, J.A. (comp.). USDA Forest Service Gen. Tech. Rep. NC-113, USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Burrill, E.A., A.M. Wilson, J.A. Turner, S.A. Pugh, J. Menlove, G. Christiansen, B.L. Conkling, and W. David. 2018. The forest inventory and analysis database: Database description and user guide version 8.0 for Phase 2. USDA Forest Service. 946 p. Available online at http://www.fia.fs.fed.us/library/database-documentation/; last accessed June 8, 2019.

Clatterbuck, W.K. 2006. Logging damage to residual trees following commercial harvesting to different overstory retention levels in a mature hardwood stand in Tennessee. P. 591–594 in *Proceedings of the 13th biennial southern silvicultural research conference*, Connor, K.F. (ed.). USDA Forest Service Gen. Tech. Rep. SRS-92, Southern Research Station, Asheville, NC.

Conrad, J.L., D.W. Greene, and P. Hiesl. IV 2018. The evolution of logging businesses in Georgia 1987–2017 and South Carolina 2012–2017. *For. Sci.* 64(6):671–681.

Erdmann, G.G., J.A. Mattson, and R.A. Oberg. 1986. A 9-year evaluation of mechanized thinning in northern hardwoods. P. 54–68 in *Hardwood thinning opportunities in the Lake States: Proceedings of a symposium*, Sturos, J.A. (comp.). USDA Forest Service Gen. Tech. Rep. NC-113, USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Dai, J., Z. Li, and D. Rocke. 2006. Hierarchical logistic regression modeling with SAS GLIMMIX. P. 9 in *Proceedings of the Thirty-first Annual SAS Users Group International Conference*. SAS Institute, Inc., Cary, NC.

Fralish, J.S. 2003. *The central hardwood forest: Its boundaries and physiographic provinces.* USDA Forest Service General Technical Report NC-234, North Central Research Station, St. Paul, MN.

Holmes, T.P. 2016. Financial and economic analysis of reduced impact logging. P. 15 in *Tropical forestry handbook*. 2nd ed. Pancel, L., and M. Kohl (eds.). Springer, Dordrecht, The Netherlands.

Lamson, N.I., H.C. Smith, and G.W. Miller. 1984. *Residual stocking not seriously reduced by logging damage from thinning of West Virginia cherry-maple stands.* USDA Forest Service Res. Pap. NE-541, Northeastern Forest Experiment Station, Broomall, PA. 7 p.

LeDoux, C.B. 2011. *Harvesting systems for the northern forest hardwoods.* USDA Forest Service Gen. Tech. Rep. NRS-91, Northern Research Station, Newton Square, PA. 65 p.

Lentini, M.W., J.C. Zweede, and T.P. Holmes. 2010. Measuring ecological impacts from logging in natural forests of the eastern Amazonia as a tool to assess forest degradation. Forest Resources Assessment Working Paper 165. Food and Agriculture Organization of the United Nations, Rome, Italy.

Luppold, W.G., and M.S. Bumgardner. 2018. Structural changes in the growing stock of important tree species groups in the Central Hardwood region. *J. For.* 116(5):405–411.

Meadows, J.S. 1993. Logging damage to residual trees following partial cutting in a green ash-sugarberry stand in the Mississippi Delta. P. 249–260 in *Proceedings of the 9th central hardwood forest conference*, Gillespie, A.R., Parker, G.A., Pope, P.E., and Rink, G. (eds.). USDA Forest Service, Southern Forest Experiment Station, Asheville, NC.

Nyland, R.D. 1989. Logging damage. P. 8.02 in *Central hardwood notes*, Clark, F.B., and J.G. Hutchinson (eds.). USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Oswalt, C.M., and R.C. Conner. 2011. *Southern forest inventory and analysis volume equations user's guide.* USDA Forest Service Gen. Tech. Rep. SRS-138. USDA Forest Service, Southern Research Station, Asheville, NC. 22 p.

Pugh, S.A., J.A. Turner, E.A. Burrill, and W. David. 2018. The forest inventory and analysis database: Population estimation user guide (Edition: November, 2018). USDA Forest Service. Available online at http://www.fia.fs.fed.us/library/database-documentation/; last accessed May 5, 2019.

SAS Institute, Inc. 2011. SAS/STAT 9.3 user's guide. SAS Institute, Inc., Cary, NC. Available online at https://support.sas.com/documentation/cdl/en/qcug/63964/PDF/default/qcug.pdf; last accessed June 26, 2019.

Shigo, A.L. 1966. *Decay and discoloration following logging wounds on northern hardwoods.* USDA Forest Service Res. Pap. NE-47, Northeastern Forest Experiment Station, Upper Darby, PA. 43 p.

Smith, D.M., B.C. Larson, M.J. Kelty, and P.M.S. Ashton. 1997. *The practice of silviculture: Applied forest ecology.* John Wiley and Sons, Inc., New York. 537 p.

USDA Forest Service. 2016. Forest inventory and analysis national core field guide. Volume I: Field data collection procedures for phase 2 plots, version 7.0. USDA Forest Service, Forest Inventory and Analysis Program, Knoxville, TN. 308 p. Available online at https://www.fs.usda.gov/srsfia/data_acquisition/SRS%20FINAL%207.0%20completeLEGAL.pdf; last accessed June 10, 2019.

US Environmental Protection Agency. 2013. Level III ecoregions of the continental United States: Corvallis, Oregon, U.S. EPA—National Health and Environmental Effects Research Laboratory, map scale 1:7,500,000. Available online at https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states; last accessed May 29, 2019.

Woodall, C.W., L.S. Heath, G.M. Domke, and M. Nichols. 2011. *Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010.* USDA Forest Service Gen. Tech. Rep. NRS-88, Northern Research Station, Newtown Square, PA. 30 p.