United States Department of Agriculture

# Selecting a Minimum Diameter for Forest Biomass and Carbon Estimation: How Low Should You Go?

Coeli M. Hoover and James E. Smith

Forest Service Northern Research Station General Technical Report NRS - 196 August 2020

## Abstract

Forest inventories are traditionally designed to produce estimates of merchantable timber volume but are increasingly used to estimate stand-level biomass or carbon. Since inventory is volume-focused, it is common practice to tally stems 5 inches and greater in diameter (at breast height; d.b.h.). When estimating carbon or biomass, practitioners may be concerned about the effect of omitting smaller stems from the inventory. We present summaries to provide indicators of when smaller diameters may be less important for an accurate estimate to assist those foresters considering adding carbon estimates to traditional inventory objectives. Small stems (e.g., 2 or 3 inches d.b.h.) may contribute appreciable biomass within a few specific types of forest stands, such as for spruce-fir or lodgepole pine, but generally the contribution is minor. Similarly, the 5- or 6-inch stems, which are moderately large for some stands, will contribute very little to stand biomass for some forest types, particularly in western forests (e.g., Douglas-fir and ponderosa pine). These are well known patterns, and we suggest such information be used to inform the choice of minimum tally diameter. Pragmatic threshold values vary by region because the importance of smaller stems is not fixed at a single diameter over all U.S. forests.



Key words: tally tree diameter, forest inventory, forest-type group


## The Authors


COELI M. HOOVER is a research ecologist and JAMES E. SMITH is a research plant physiologist, Northern Research Station, 271 Mast Road, Durham, NH 03824


## Cover Photo

Mixed hardwood-oak small pole stand, in the Massabesic Experimental Forest, Lyman, ME. Photo by Mariko Yamasaki, USDA Forest Service.

## Quality Assurance

This publication conforms to the Northern Research Station's Quality Assurance Implementation Plan which requires technical and policy review for all scientific publications produced or funded by the Station. The process included a blind technical review by at least two reviewers, who were selected by the Assistant Director for Research and unknown to the author. This review policy promotes the Forest Service guiding principles of using the best scientific knowledge, striving for quality and excellence, maintaining high ethical and professional standards, and being responsible and accountable for what we do.


Manuscript received for publication October 1, 2018.

Published by
USDA FOREST SERVICE
ONE GIFFORD PINCHOT DRIVE
MADISON, WI 53726

AUGUST 2020

# INTRODUCTION

Over time, there have been many technological and protocol and sampling advances to make the forest inventory process more efficient and accurate. Yet for many field foresters that routinely perform or otherwise engage in forest inventories, it is easy to overlook the information quality and cost tradeoffs that are inherent in the design of the inventory system being used. An ongoing series in "The Forestry Source," Biometric Bits, (for example, Pond 2017) discusses many of these issues, ranging from fixed- versus variable-radius plots, to choosing how much information to collect. The Biometric Bits series provides a good illustration of the many facets of inventory design. Here, we address one aspect of information collected, specifically, the varying importance of small diameter stems to forest stand biomass (or carbon) estimation.

Standard forest inventory protocols generally focus on estimating forest stand-level volume and often focus on merchantable timber volume. The historical purpose of forest inventory has been to assess the amount of merchantable volume available for sale and to provide information for future harvest scheduling and needs. While the general approach to stand inventory is fairly consistent, actual "rules" are rare. Instead, guidelines are available from which landowners and managers may choose the inventory practices that will meet their needs efficiently and with the desired level of accuracy. A classic text, "Forest Inventory" (Spurr 1952), provides detailed discussions of multiple approaches to estimating stand volume, predicting growth, and designing the inventory. Lund and Thomas (1989) provide a thorough overview of the many options possible and the tradeoffs among them. On one point, though, both Spurr and Lund and Thomas are silent: the appropriate minimum diameter threshold for trees to include in the inventory.

Merchantability, also known as commercial acceptability, is defined differently for different forest types and geographic regions, which is perhaps why no guidelines on minimum stem diameter exist. Many volume tables[1] begin at 4 or 5 inches diameter at breast height (d.b.h.; 4.5 feet above ground), a commonly used merchantability threshold. The USDA Forest Service Forest Inventory and Analysis Program (FIA) (USDA Forest Service 2018) uses an inventory approach with nested plots, which tallies stems less than 5 inches d.b.h. within the smaller-radius subplots. However, the FIA inventory is designed to provide a comprehensive assessment of U.S. forest resources and is not intended for operational use (though, resources permitting, the FIA protocol could be applied for routine inventory).

While the attention to merchantable volume makes sense in the framework of sustainable timber production, today's forest inventories may be conducted in support of additional objectives. For example, carbon credit and greenhouse gas offset projects require estimates of carbon in live biomass, while bioenergy programs may need assessments of biomass in smaller diameter classes that may not be tallied in a conventional inventory. The choice of diameter threshold becomes more complicated in these situations—omitting smaller stems may have important effects on biomass estimates in some forest types and regions, but including smaller trees increases the time and cost of inventory. Despite this, there has been little research on the appropriate minimum diameter for forest inventories conducted for reasons other than (or in addition to) assessing merchantable volume of timber.

[1] A volume table refers to a chart to estimate standing timber volume. The tables are based on volume equations and use correlations between certain aspects of a tree to estimate the volume to a degree of certainty. The diameter at breast height (d.b.h.) and the merchantable height are used to determine the total volume.

Many European nations have national forest inventory programs with designs that vary by country. A recent review of the forest inventory programs of 29 nations showed that minimum diameter for inclusion ranged from 0 to 4.7 inches (0 to 12 cm), with 0, 2, 2.7, and 3 inches (0, 5, 7, and 7.5 cm) the most common minimum diameter values (Gschwanter et al. 2016); efforts are underway to harmonize inventory programs among European nations (McRoberts et al. 2009, Winter et al. 2008). Keränen et al. (2015) investigated the effects of diameter thresholds in the context of LiDAR-based forest inventory approaches in Finland. They calculated volume and biomass for sample plots in managed young, middle-age, and mature forests using minimum tree diameters from 1.2 to 3.9 inches (3 to 10 cm). They report that minimum diameter did not affect the accuracy of the volume or biomass estimates in middle-age and mature stands. However, use of a larger minimum diameter did have a pronounced effect on results from young stands: percent root mean square error (RMSE %) for the aboveground biomass estimate increased from 23.7 at a minimum d.b.h. of 1.2 inches (3 cm) to 39.0 when using a 4-inch (10 cm) diameter threshold.

We are often contacted by practitioners (e.g., consultants and state extension personnel) who are interested in adding carbon estimates to the services they can provide to clients. A common inventory approach consists of prism-based variable-radius plots. These variable-radius plots are less common for estimating carbon stocks over time than permanent fixed-radius plots because most forest carbon offset projects require third-party verification at specified intervals for the duration of the project, a requirement that is facilitated using a permanent fixed-radius protocol. Many practitioners are reluctant to employ a permanent plot approach often because they assume that an FIA-type design may be necessary, with the associated perception that tallying many stems on large plots is the requirement. Some practitioners conclude that fixed-area plots are likely to result in increased time and cost and will not produce enough return on the investment. These assumptions are not necessarily true: a simple fixed-area plot with an appropriate tree-diameter threshold can be efficient, resulting in increased information at little additional cost.[2] This approach can be adjusted to include tallying of stems below the threshold on a smaller subplot if desired.

Our objective is to assist practitioners who may be considering adding carbon estimates to the services they provide, or who may be curious about the practical implications of using a fixed-area plot approach. Bearing in mind the increased cost of using a smaller tree-diameter threshold and the lack of available information on potential benefits, we ask a straightforward question: How is biomass distributed among the smaller diameter classes? Is this distribution different between hardwoods and softwoods, or geographic regions of the United States? Because forest inventories may be conducted to meet different information needs or management objectives, our goal is not to make specific recommendations but to provide practitioners with information that will enable them to select a pragmatic minimum diameter threshold that is appropriate for their needs.

## Methods

Summaries are based on FIA forest inventory data, which were obtained from the publicly available DataMart (USDA Forest Service 2018) on 31 October 2018. Data are from forested plots of the 48 conterminous states and the approximate 12 percent of Alaska forest land

[2] Personal communication, Steve Bick, Northeast Forests, LLC


Figure 1.—Geographic regions used for summarizing data. See also Hoover et al. 2014. The eastern and western regions are distinguished by the bold line.

(southern coastal Alaska) that has been fully sampled on the grid of permanent FIA inventory plots. The inventory area and states and regions used for summarizing the data are illustrated in Figure 1 (Hoover et al. 2014).

Single inventory cycles, the most recent per state, are summarized from the downloaded FIA data and used for this analysis. Plot selection is further filtered to include only plots with 50 percent or more forested condition, by area (see O'Connell et al. 2017 for details on inventory plots and data fields). The majority of data summarized here (including all figures) are based on plots where all tally trees' diameters were measured at breast height (d.b.h.). However, where explicitly noted as woodland type groups, selected tabular summaries are based on plots where all tally trees' diameters were measured at root collar (d.r.c.) (see Table 1, footnote b). We exclude plots with mixed breast-height and root-collar diameters because pooling two very different diameter-biomass relationships is not informative. Carbon mass of individual tally trees and total forest stand density are based on aboveground carbon estimates of Chojnacky et al (2014). Figures 2 through 5 present results as a percentage of mean total stand carbon summarized according to tree diameter bins. In accordance with standard field practice, the diameter class represents the midpoint of the diameter bin so for example, the 2-inch size class includes stems from 1.50 to 2.49 inches d.b.h.

**Table 1.—Mean percentage of aboveground forest stand live tree carbon stock in trees with diameters (d.b.h.) less than 5 inches**

| Region | Forest-type group[a] | Mean percentage of carbon stock in trees less than 5-inch diameter[b] | | |
|---|---|---|---|---|
| | | Softwood | Hardwood | All species[c] |
| Coastal Alaska | Spruce-fir | 33 | 1 | 34 |
| | Fir-spruce-mountain hemlock | 4 | <1 | 4 |
| | Hemlock-Sitka spruce | 2 | <1 | 2 |
| | Aspen-birch | 5 | 4 | 9 |
| Pacific Northwest–West | Douglas-fir | 1 | <1 | 1 |
| | Fir-spruce-mountain hemlock | 2 | <1 | 2 |
| | Hemlock-Sitka spruce | 1 | <1 | 1 |
| | Alder-maple | 1 | 2 | 2 |
| Pacific Northwest–East | Douglas-fir | 2 | <1 | 2 |
| | Ponderosa pine | 2 | <1 | 2 |
| | Fir-spruce-mountain hemlock | 3 | <1 | 3 |
| | Lodgepole pine | 14 | <1 | 14 |
| | Other western softwoods | 3 | <1 | 3 |
| Pacific Southwest | Ponderosa pine | 1 | <1 | 1 |
| | Fir-spruce-mountain hemlock | 1 | <1 | 1 |
| | Other western softwoods | 2 | <1 | 2 |
| | California mixed conifer | 1 | <1 | 2 |
| | Western oak | <1 | 4 | 5 |
| | Tanoak-laurel | <1 | 3 | 3 |
| Rocky Mountain–North | Douglas-fir | 3 | <1 | 3 |
| | Ponderosa pine | 3 | <1 | 3 |
| | Fir-spruce-mountain hemlock | 5 | <1 | 5 |
| | Lodgepole pine | 10 | <1 | 10 |
| Rocky Mountain–South | Pinyon-juniper[b] | 2 | <1 | 3 |
| | Ponderosa pine | 2 | <1 | 2 |
| | Fir-spruce-mountain hemlock | 4 | <1 | 5 |
| | Lodgepole pine | 11 | <1 | 11 |
| | Aspen-birch | 1 | 5 | 6 |
| | Woodland hardwoods[b] | 1 | 19 | 19 |
| Great Plains | Pinyon-juniper[b] | 10 | 1 | 11 |
| | Oak-hickory | <1 | 7 | 7 |
| | Elm-ash-cottonwood | <1 | 5 | 5 |
| | Woodland hardwoods[b] | <1 | 11 | 12 |
| Northern Lake States | White-red-jack pine | 4 | 3 | 7 |
| | Spruce-fir | 20 | 3 | 22 |
| | Oak-hickory | <1 | 5 | 6 |
| | Elm-ash-cottonwood | 1 | 8 | 9 |
| | Maple-beech-birch | 1 | 5 | 6 |
| | Aspen-birch | 3 | 17 | 20 |
| Central States | Oak-pine | 2 | 6 | 8 |
| | Oak-hickory | <1 | 5 | 5 |
| | Elm-ash-cottonwood | <1 | 4 | 4 |
| Northeast | White-red-jack pine | 2 | 2 | 4 |
| | Spruce-fir | 19 | 4 | 23 |
| | Oak-hickory | <1 | 4 | 4 |
| | Elm-ash-cottonwood | 1 | 6 | 7 |
| | Maple-beech-birch | 1 | 6 | 8 |

| Region | Forest-type group[a] | Mean percentage of carbon stock in trees less than 5-inch diameter[b] | | |
|---|---|---|---|---|
| | | Softwood | Hardwood | All species[c] |
| South Central | Loblolly-shortleaf pine | 3 | 5 | 8 |
| | Oak-pine | 2 | 8 | 10 |
| | Oak-hickory | <1 | 7 | 7 |
| | Oak-gum-cypress | <1 | 5 | 5 |
| | Elm-ash-cottonwood | <1 | 6 | 6 |
| Southeast | Longleaf-slash pine | 4 | 3 | 6 |
| | Loblolly-shortleaf pine | 3 | 5 | 9 |
| | Oak-pine | 1 | 8 | 9 |
| | Oak-hickory | <1 | 5 | 6 |
| | Oak-gum-cypress | 1 | 6 | 7 |

[a]Forest-type groups (within regions) are included if they represent at least 4 percent of forest within the region based on plot selection used here.

[b]Stem diameters of most species are measured at breast height. However, inventory plots selected to summarize woodland type groups for this analysis (pinyon-juniper and woodland hardwoods) have all tally tree stem diameters measured at root collar (O'Connell et al. 2017).

[c]Note that the sum of the softwood and hardwood stem columns may not equal value in total column due to rounding.

# Results

## Carbon Distribution in Smaller Stems: Regional Patterns

The cumulative distribution of carbon in live aboveground tree biomass at the forest stand level follows a typical pattern, with a small proportion of carbon contained in the smaller diameter classes. Although this pattern is similar in the eastern and western United States, there are a few notable differences. In the eastern United States[3], the percentage of aboveground live tree carbon represented by stems, up to and including the 8-inch d.b.h. class, ranges from 19 to 32 percent, with much of the carbon in hardwoods (Figure 2). Hardwood and softwood type group classes provide additional resolution in those instances where a user may be working in stands composed primarily of hardwoods or softwoods. Differences between hardwoods and softwoods are evident. In the South Central region (Figure 2D), for example, hardwood stems up to the 4-inch class represent about 6 percent of stand carbon, while that same proportion of contribution by softwoods requires trees up to the 7-inch class.

In the western United States[4], the percentage of live tree carbon in stems up to and including the 8-inch class varies from 7 to 23 percent, most of which is represented by softwoods (Figure 3), with the exception of the Pacific Southwest region (Fig. 3E). Appendix 1 (Tables 3–14) provide mean carbon tons per acre corresponding to the diameter bins in Figures 2 and 3.

## Exceptions to Regional Results: Role of Forest Type

The regional patterns illustrated in Figures 2 and 3 can obscure useful diameter distributions characteristic of some individual forest-type groups. A notable instance is in the Pacific

[3] Figure 2 shows regions from Figure 1 that we refer to as "eastern United States": Northeast, Southeast, Central States, South Central, and Northern Lake States.

[4] Figure 3 shows regions that, for purposes of this paper, we refer to as "western United States": Rocky Mountain–North, Rocky Mountain–South, Pacific Northwest–East, Pacific Northwest–West, and Pacific Southwest.

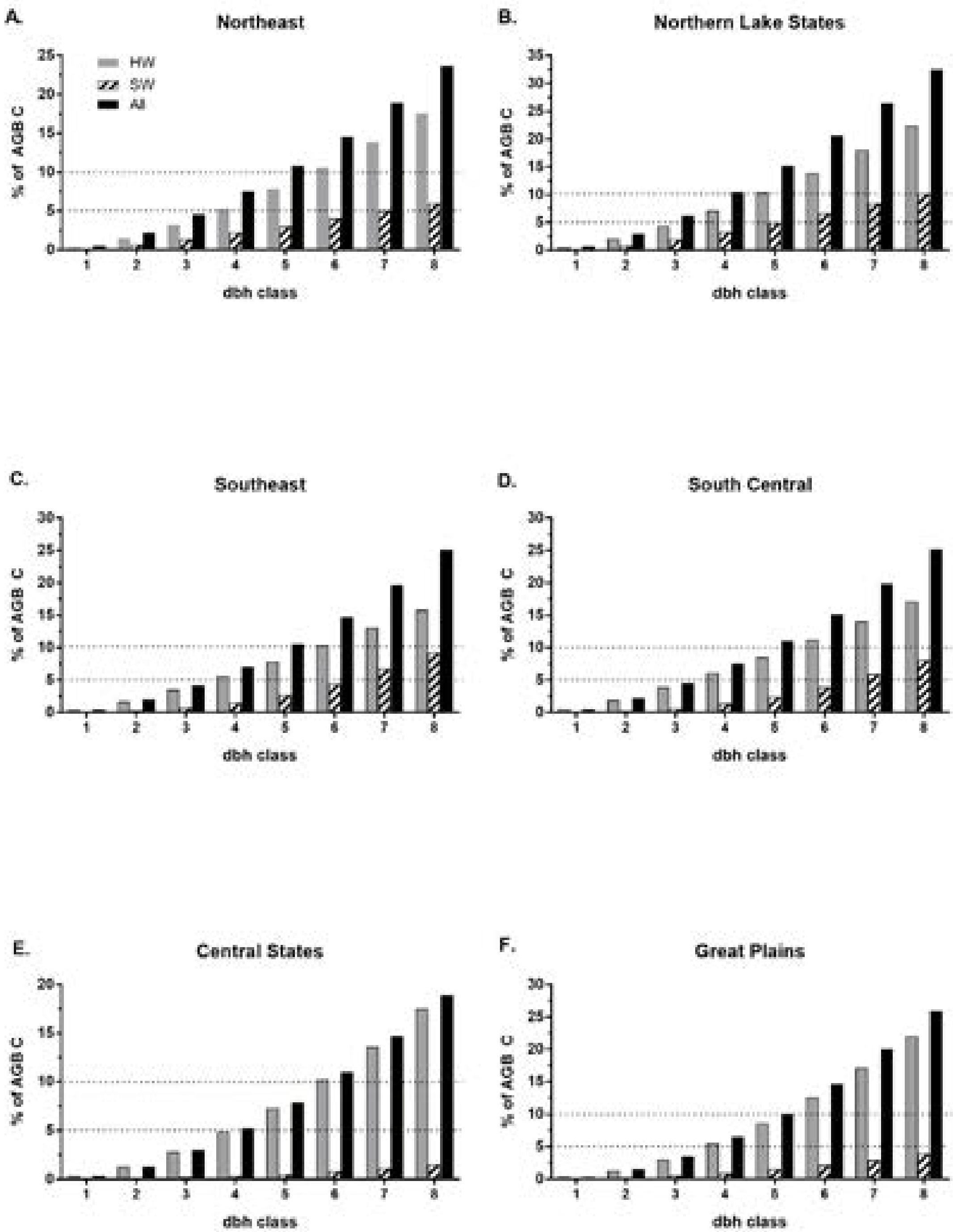


Figure 2.—Cumulative percentage of carbon in live aboveground tree biomass (AGB C) represented by smaller diameter trees in the “eastern” regions for hardwoods, softwoods, and the sum (All in legend) of the two groups. Note that bin number represents the midpoint of the diameter class. Dashed lines indicate 5 and 10 percent of plot level carbon stock, provided for reference. Note that y-axis scale in Figure 2 varies for each region.

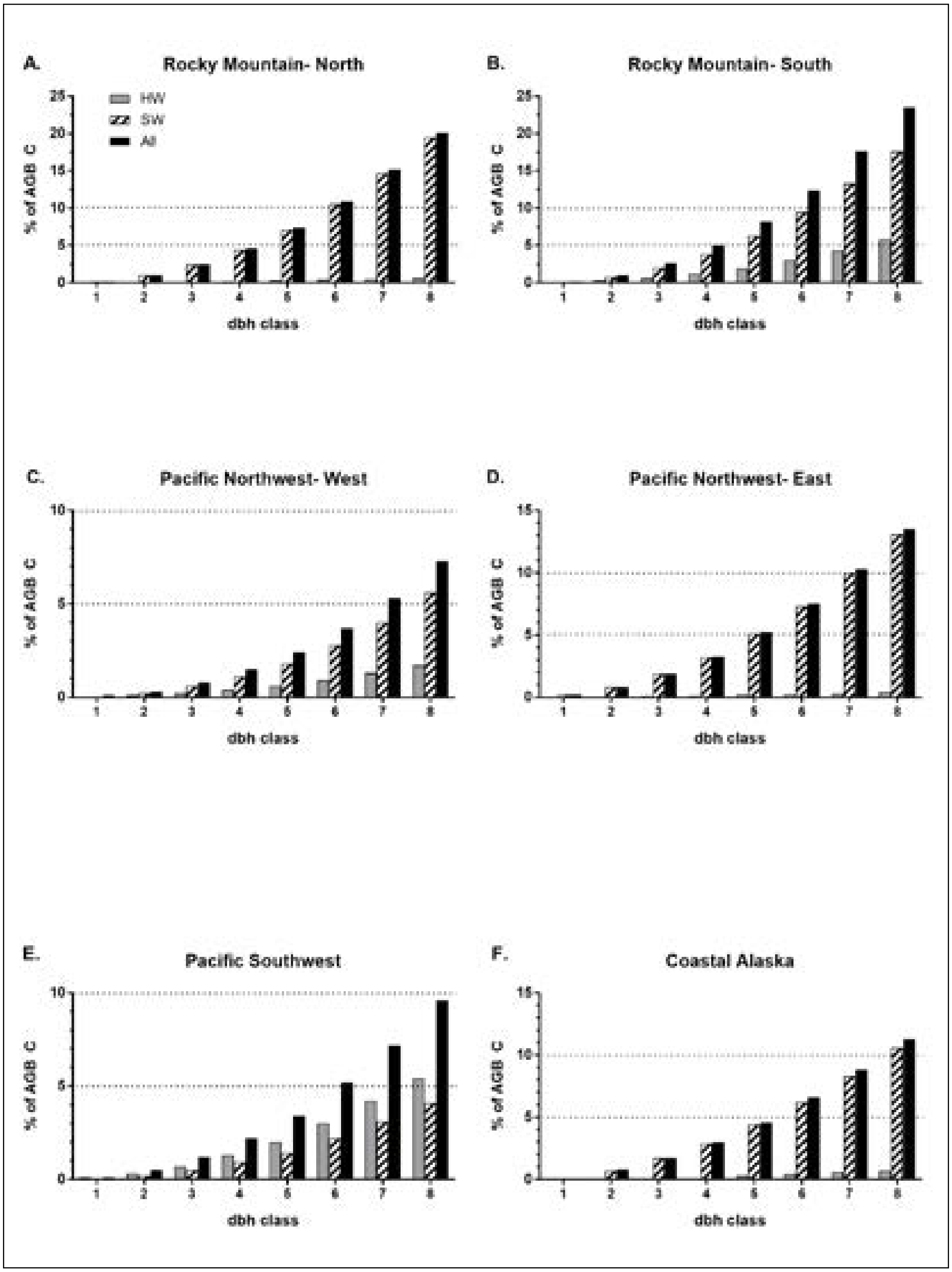


Figure 3.—Cumulative percentage of carbon in live aboveground tree biomass (AGB C) represented by smaller diameter trees in the western regions for hardwoods, softwoods, and sum of the two groups (All in legend). Note that bin number represents the midpoint of the diameter class. Dashed lines indicate 5 and 10 percent of plot level carbon stock, provided for reference. Note that y-axis scale in Figure 3 varies for each region.

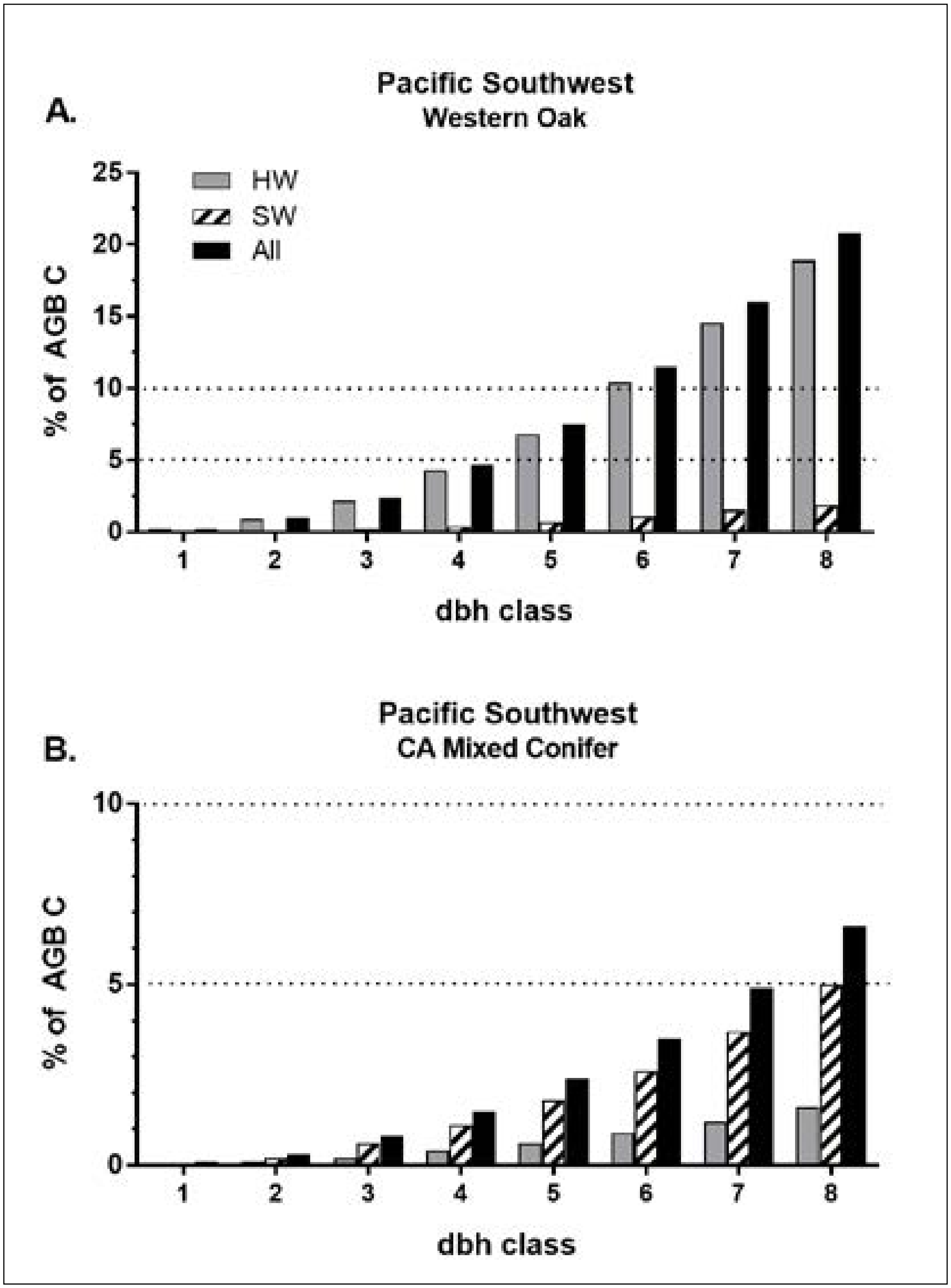


Figure 4.—Cumulative percentage of carbon in live aboveground tree biomass (AGB C) represented by smaller diameter (<8.49 inch d.b.h.) trees in the Pacific Southwest Region, for hardwoods, softwoods, and sum of the two groups (All in legend). Graph A (hardwood dominated) and Graph B (softwood dominated) illustrate the two distinct patterns present in this region. Note that bin number represents the midpoint of the diameter class. Dashed lines indicate 5 and 10 percent of plot level carbon stock, provided for reference.

Southwest, where the regional overview (Figure 3E) reflects greater relative balance between softwood and hardwood contribution than is generally the case in the West. However, the significant proportion of hardwood-dominated forest-type groups in the Pacific Southwest region (over one-third of forest) (U.S. EPA 2015) results in a regional average different from that of the component type groups. The tanoak-laurel forest-type group is similar to the western oak distribution shown in Figure 4A, while the fir-spruce-mountain hemlock, other western softwoods, and ponderosa pine type groups follow the California mixed conifer results shown in Figure 4B. Appendix 2 (Tables 15 and 16) provide mean carbon tons per acre corresponding to the diameter bins in Figure 4.

In the Central States, Great Plains, Rocky Mountain- North, and Pacific Northwest- East regions, all of the forest-type groups investigated resemble the regional results (Figures 2E, 2F, 3A, and 3D, respectively). In other regions there are some exceptions, generally in forest-type groups with a large component of stems that differs from the predominant cover type in the region. In the Northeast, tree carbon is predominantly represented by hardwood stems (Figure 2A); however, in the spruce-fir group most carbon is found in softwoods, and smaller size classes contribute a larger proportion of the total than in other types (Figure 5A). This pattern also is evident in spruce-fir and white-red-jack pine in the Northern Lake States, while other type groups in the Northeast region follow the general pattern shown in Figures

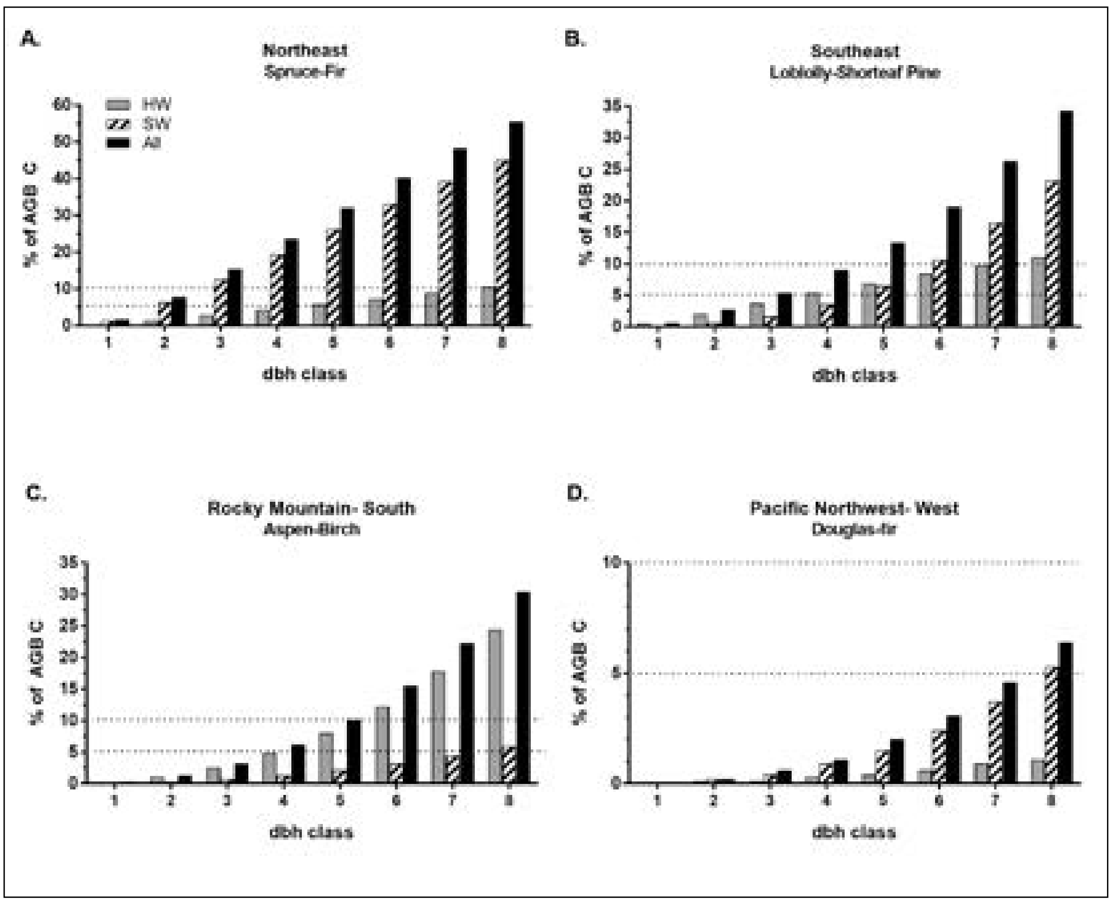


Figure 5.—Cumulative percentage of carbon in live aboveground tree biomass (AGB C) represented by smaller diameter trees in selected forest-type groups and regions for hardwoods, softwoods, and the sum of the two groups (All in the legend). Note that bin number represents the midpoint of the diameter class. Dashed lines indicate 5 and 10 percent of plot level carbon stock, provided for reference.

2A and 2B. In the Southeast (Figure 2C), loblolly-shortleaf pine and longleaf-slash pine are the exceptions, with more carbon in softwood stems (Figure 5B); loblolly-shortleaf pine in the South Central region displays similar behavior, while the other groups resemble the regional pattern. The remaining exceptions are hardwood forest-type groups found within the predominantly softwood regions of Rocky Mountain–South (aspen-birch), Pacific Northwest–West (alder-maple), and Coastal Alaska (aspen-birch), all of which resemble Figure 5C. The final forest-type group example, Douglas-fir (Figure 5D), is not an exception but is included because of its ecological and economic importance in the region. Appendix 3 (Tables 17–20) provide mean carbon tons per acre corresponding to the diameter bins in Figure 5.

## Discussion

### Practical Implications

The purpose of this work is not to provide specific recommendations with respect to sampling or plot design because these decisions are based on information needs, site characteristics, and landowner objectives. However, it is intended as an overview of stand attributes generally consistent within region or forest-type group that are useful to consider where inventory objectives include an assessment of carbon (or biomass) but detailed biomass estimates are not sought given the additional resource requirements associated with more intense inventories (more time, people, cost). When the estimation of the carbon/biomass associated with the small stems becomes important, accurate estimates representing total carbon contributed by all stems are generally possible via regressions on the more important (or characteristic) larger stems. Similarly, estimating change also is an important component of carbon inventory (one of the reasons for the emphasis on fixed-radius plots), and sufficiently characterizing the plot in order to estimate growth is important when considering a threshold diameter. This additional need to address change in carbon over time necessitates additional consideration of what stem sizes to measure (as a function of type or region); this set of procedures is not addressed here but is a focus of current research.

Our objective is to illustrate the variable contribution of lower diameter classes to forest stand-level carbon stocks. The dotted lines on figures indicating the 5 and 10 percent levels is for ease of comparison across regions and are not meant to imply any particular recommendation since the appropriate threshold diameter for inventory will depend on the user's particular needs. However, these results can inform the inventory design process. For example, in eastern forest stands, stems in the 3- and 4-inch classes (depending on region) could generally be omitted without sacrificing resolution, while in some western forest stands a 6-inch threshold may be appropriate. Note that stand size class is also a factor to consider; these general patterns will be less applicable if a stand has a high proportion of saplings and poletimber. In this case, smaller stems will comprise a larger share of stand biomass. As noted previously, in spruce-fir types these smaller classes make a noticeable contribution to the total and would likely be included in the tally. In certain cases, such as in some western regions, all hardwood stems smaller than 8 inches d.b.h. could probably be excluded from inventory with no appreciable impact on the stand-level estimate (see in particular, Rocky Mountain–North or Pacific Northwest–East).

Tradeoffs between the time required to inventory smaller size classes and the value of that added information are evaluated by a landowner conducting an inventory where the data will be used for multiple purposes (e.g., carbon stocks and merchantable timber volume). The information presented here can assist in that process. Since volume tables are generally based on stems that are 5 inches d.b.h. and greater, we also have summarized the data to show the average percentage of carbon stock (by region and forest-type group) represented by trees 5 inches d.b.h. and smaller (Table 1), which is useful when considering adding carbon as an additional management objective to a sustainable timber program. It is apparent that in most regions and forest types, carbon (and biomass) represented in trees under 5 inches d.b.h. is a small proportion of the stand-level stock, with a few notable exceptions: spruce-fir and lodgepole pine, regardless of region, and aspen-birch in the Northern Lake States.

Forest stands composed primarily of small-diameter stems, which often are also high density, can be challenging to inventory efficiently. Examples of such stands can include young plantations or some naturally regenerating areas where most stems will be subject to mortality while still small. The approach of a "minimum tally diameter" is not useful for developing carbon stock estimates in these cases with uniformly small stems. However, as stands mature, identifying likely survivors and developing estimates based on those stems is a potential size-based approach to estimates, but is beyond the scope of the discussion here.

## An Additional Perspective on Regional Patterns

While the percentages of carbon by diameter class presented in Figures 2 through 5 and Table 1 can help inform inventory decisions, it may be challenging to envision how those differences are expressed at the parcel level. To provide a practical illustration of the effects of different diameter threshold values, we compiled FIA data from selected national forests in different geographic regions and estimated per-acre carbon storage for common forest-type groups using a variety of diameter thresholds as examples. This per-acre value is also expressed as an areawide stock for parcels of 20 and 40 acres. While this is a simplified example, it illustrates the effect of smaller and larger per-area differences as well as parcel size. In the instance of spruce-fir in the Northeast region, the difference in the live aboveground carbon stock between tallying stems >1 inch versus 2 inches d.b.h. is 0.43 tons C/ac but increases to 3.95 tons/ac when the tally excludes stems under 4 inches d.b.h. Referring to Table 2, we can see that for a 20-acre parcel, this would translate to a difference in the parcel-wide carbon stock of 9 tons if using a 2-inch threshold, or 79 tons if the threshold is 4 inches (about 12 percent of the estimate). For a parcel of 40 acres, this translates to 18 and 250 tons for a 2- or 4-inch threshold, respectively.

In contrast, using a Douglas-fir dataset from the Pacific Northwest shows a difference of 0.03 tons C/ac when moving from a 1- to a 2-inch d.b.h. tally threshold, which increases to just 0.48 tons C/ac when stems 4 inches d.b.h. and greater are tallied. For 20 acres, this amounts to a difference in the parcel-wide stock of 0.6 tons if using a 2-inch minimum and 9.6 tons if tallying stems 4 inches d.b.h. and greater. On a 40-acre parcel, this difference would amount to 1 ton for the 2-inch threshold, and 19 tons (which represents about 0.50 percent of the total stock estimate) if including trees in the 4-inch d.b.h. class and above. These two forest types represent the ends of the range of the effect of smaller diameter classes on a stand level carbon stock estimate. For most forest types, the outcome is intermediate (Table 2).

Table 2.—Examples of aboveground live tree carbon estimates for different diameter thresholds and parcel sizes. Standard error of per-acre estimate is in parentheses; N is the number of plots included.

| Region | Forest-type group | d.b.h. threshold (inches) | tons live tree C/acre | N | tons live tree C | |
|---|---|---|---|---|---|---|
| | | | | | 20 acres | 40 acres |
| Northeast | Spruce-fir | all stems | 32.1 (0.89) | 99 | 643 | 1286 |
| | | 2 | 31.7 (0.91) | 99 | 634 | 1268 |
| | | 3 | 30.2 (0.94) | 99 | 604 | 1127 |
| | | 4 | 28.2 (0.98) | 99 | 564 | 1036 |
| | | 5 | 25.9 (0.98) | 99 | 518 | 1209 |
| Southeast | Loblolly-slash pine | all stems | 38.0 (1.88) | 68 | 759 | 1519 |
| | | 2 | 37.9 (1.88) | 68 | 758 | 1515 |
| | | 3 | 37.4 (1.89) | 68 | 749 | 1498 |
| | | 4 | 36.7 (1.89) | 68 | 733 | 1466 |
| | | 5 | 35.8 (1.90) | 68 | 715 | 1430 |
| Southeast | Oak-hickory | all stems | 37.4 (1.98) | 86 | 747 | 1495 |
| | | 2 | 37.3 (1.88) | 86 | 746 | 1491 |
| | | 3 | 36.8 (1.99) | 86 | 737 | 1474 |
| | | 4 | 36.3 (2.01) | 86 | 726 | 1452 |
| | | 5 | 35.5 (1.98) | 86 | 710 | 1421 |
| Pacific Northwest–West | Douglas-fir | all stems | 88.6 (5.14) | 112 | 1772 | 3545 |
| | | 2 | 88.6 (5.14) | 112 | 1772 | 3544 |
| | | 3 | 88.4 (5.16) | 112 | 1768 | 3536 |
| | | 4 | 88.1 (5.21) | 112 | 1763 | 3525 |
| | | 5 | 87.5 (5.28) | 110 | 1751 | 3501 |
| Rocky Mountain–South | Lodgepole pine | all stems | 24.9 (1.63) | 46 | 498 | 995 |
| | | 2 | 24.9 (1.63) | 46 | 497 | 994 |
| | | 3 | 24.6 (1.59) | 46 | 493 | 986 |
| | | 4 | 24.0 (1.62) | 46 | 479 | 959 |
| | | 5 | 22.6 (1.48) | 45 | 452 | 903 |

## Conclusions

Land managers and landowners are becoming increasingly interested in quantifying the carbon stored in their forests, providing additional opportunities for foresters. However, carbon inventories are generally conducted on permanent fixed-area plots to facilitate estimating change over time (monitoring and verification are important components of most carbon offset programs). Forest inventory is often focused on estimating merchantable timber volume and is conducted using a prism. Practitioners can be reluctant to consider a fixed-area inventory design out of concern that the additional time and effort will not be justified. We suggest that inventory time and cost can be reduced by choosing a minimum tree diameter in the inventory that is appropriate to the forest type and user's information needs, rather than tallying all trees above 1 inch d.b.h. While the data presented here are not obtained from forest stand-level inventories and will have somewhat different error properties than smaller local samples, we have observed the same patterns in stand inventory data (prompting this more systematic assessment). Regional summaries of carbon by tree diameter class provide empirical information to which practitioners can refer when considering the tradeoffs of implementing a fixed-radius versus variable-radius plots, and to assist in choosing a pragmatic tree diameter threshold when designing an inventory in which carbon estimation is among the objectives.

## Acknowledgments

The authors are grateful to Steve Bick, Mariko Yamasaki, and James Long for feedback on this manuscript. We also appreciate the insightful suggestions of two anonymous reviewers, which also improved the manuscript.

## Literature Cited

Chojnacky, D.C.; Heath, L.S.; Jenkins, J.C. 2014. **Updated generalized biomass equations for North American tree species.** Forestry. 87(1): 129-151. https://doi.org/10.1093/forestry/cpt053.

Gschwanter, T.; Lanz, A.; Vidal, C.; Bosela, M.; DiCosmo, L. [et al.]. 2016. **Comparison of methods used in European national forest inventories for the estimation of volume increment: towards harmonization.** Annals of Forest Science. 73(4): 807-821. https://doi.org/10.1007/s13595-016-0554-5.

Hoover, C.; Birdsey, R.; Goines, B.; Lahm, P.; Marland, G. [et al.]. 2014. **Chapter 6: Quantifying greenhouse gas sources and sinks in managed forest systems.** In: Eve, M.; Pape, D.; Flugge, M.; Steele, R.; Man, D. [et al.], eds. **Quantifying greenhouse gas fluxes in agriculture and forestry: Methods for entity-scale inventory.** Tech. Bull. 1939. Washington, DC: U.S. Department of Agriculture, Office of the Chief Economist: 6-1—6-113.

Keränen, J.; Peuhkurinen, J.; Packalen, P.; Maltamo, M. 2015. **Effect of minimum diameter at breast height and standing dead wood field measurements on the accuracy of ALS-based forest inventory.** Canadian Journal of Forest Research. 45(10): 1280-1288. https://doi.org/10.1139/cjfr-2015-0103.

Lund, H.C.; Thomas, C.E. 1989. **A primer on stand and forest inventory designs.** Gen. Tech. Rep. WO-54. Washington, DC: U.S. Department of Agriculture, Forest Service. 96 p.

O'Connell, B.M.; Conkling, B.L.; Wilson, A.M.; Burrill, E.A.; Turner, J.A. [et al.]. 2017. **The forest inventory and analysis database: database description and user guide, version 7.0 for Phase 2.** Washington, DC: U.S. Department of Agriculture, Forest Service. https://www.fia.fs.fed.us/library/database-documentation/index.php (accessed 28 June 2019).

Pond, N.C. 2017. **What is the "right" amount of inventory data to collect?** The Forestry Source. March 2017. https://blog.silviaterra.com/the-right-amount-of-inventory/ (accessed 11 March 2019).

Spurr, S.H. 1952. **Forest inventory.** New York, NY: Ronald Press Company. 476 p.

USDA Forest Service. 2018. **FIA Datamart.**
https://apps.fs.usda.gov/fia/datamart/datamart.html (accessed 31 October 2018).

USDA Forest Service. 2018. **Forest inventory and analysis national program.**
https://www.fia.fs.fed.us/ (accessed 12 July 2019).

U.S. Environmental Protection Agency [U.S. EPA]. 2015. **Inventory of U.S. greenhouse gas emissions and sinks: 1990–2013.** EPA 430-R-15-004. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs. 564 p.
https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2013 (accessed 16 April 2020).

# APPENDIX 1

Carbon stock estimates by diameter class and region, corresponding to Figures 2 and 3.

**Table 3.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter bin for hardwood stems, softwood stems, and all stems, Northeast region. This summary includes 13,212 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.12 | 0.002 |
| | 2 | 0.41 | 0.005 |
| | 3 | 0.60 | 0.008 |
| | 4 | 0.75 | 0.011 |
| | 5 | 0.87 | 0.011 |
| | 6 | 0.99 | 0.008 |
| | 7 | 1.17 | 0.010 |
| | 8 | 1.31 | 0.011 |
| Softwood | 1 | 0.05 | 0.002 |
| | 2 | 0.19 | 0.005 |
| | 3 | 0.26 | 0.007 |
| | 4 | 0.31 | 0.008 |
| | 5 | 0.34 | 0.008 |
| | 6 | 0.36 | 0.006 |
| | 7 | 0.38 | 0.007 |
| | 8 | 0.39 | 0.007 |
| All[c] | 1 | 0.17 | 0.002 |
| | 2 | 0.60 | 0.007 |
| | 3 | 0.86 | 0.011 |
| | 4 | 1.06 | 0.014 |
| | 5 | 1.20 | 0.013 |
| | 6 | 1.35 | 0.009 |
| | 7 | 1.55 | 0.011 |
| | 8 | 1.70 | 0.012 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 4.—Mean and standard error (SEM) of live aboveground carbon stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Northern Lake States region. This summary includes 13,784 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.12 | 0.002 |
| | 2 | 0.40 | 0.005 |
| | 3 | 0.55 | 0.008 |
| | 4 | 0.69 | 0.011 |
| | 5 | 0.79 | 0.011 |
| | 6 | 0.89 | 0.009 |
| | 7 | 1.00 | 0.010 |
| | 8 | 1.07 | 0.011 |
| Softwood | 1 | 0.04 | 0.001 |
| | 2 | 0.17 | 0.004 |
| | 3 | 0.26 | 0.006 |
| | 4 | 0.34 | 0.008 |
| | 5 | 0.39 | 0.008 |
| | 6 | 0.42 | 0.008 |
| | 7 | 0.44 | 0.008 |
| | 8 | 0.43 | 0.009 |
| All[c] | 1 | 0.16 | 0.002 |
| | 2 | 0.56 | 0.006 |
| | 3 | 0.81 | 0.009 |
| | 4 | 1.04 | 0.013 |
| | 5 | 1.18 | 0.013 |
| | 6 | 1.31 | 0.010 |
| | 7 | 1.45 | 0.012 |
| | 8 | 1.50 | 0.013 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 5.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Central States region. This summary includes 5,762 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.09 | 0.002 |
| | 2 | 0.34 | 0.006 |
| | 3 | 0.51 | 0.010 |
| | 4 | 0.69 | 0.015 |
| | 5 | 0.82 | 0.016 |
| | 6 | 0.97 | 0.011 |
| | 7 | 1.12 | 0.013 |
| | 8 | 1.29 | 0.015 |
| Softwood | 1 | - | - |
| | 2 | 0.01 | 0.001 |
| | 3 | 0.03 | 0.002 |
| | 4 | 0.05 | 0.003 |
| | 5 | 0.06 | 0.004 |
| | 6 | 0.08 | 0.004 |
| | 7 | 0.10 | 0.005 |
| | 8 | 0.10 | 0.005 |
| All[c] | 1 | 0.10 | 0.002 |
| | 2 | 0.36 | 0.006 |
| | 3 | 0.55 | 0.010 |
| | 4 | 0.73 | 0.015 |
| | 5 | 0.89 | 0.016 |
| | 6 | 1.05 | 0.011 |
| | 7 | 1.21 | 0.014 |
| | 8 | 1.39 | 0.016 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 6.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, South Central region. This summary includes 19,029 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.13 | 0.001 |
| | 2 | 0.41 | 0.004 |
| | 3 | 0.56 | 0.006 |
| | 4 | 0.63 | 0.008 |
| | 5 | 0.69 | 0.008 |
| | 6 | 0.76 | 0.006 |
| | 7 | 0.82 | 0.007 |
| | 8 | 0.88 | 0.008 |
| Softwood | 1 | 0.01 | - |
| | 2 | 0.05 | 0.001 |
| | 3 | 0.12 | 0.003 |
| | 4 | 0.19 | 0.005 |
| | 5 | 0.29 | 0.006 |
| | 6 | 0.41 | 0.007 |
| | 7 | 0.54 | 0.009 |
| | 8 | 0.62 | 0.010 |
| All[c] | 1 | 0.14 | 0.001 |
| | 2 | 0.47 | 0.004 |
| | 3 | 0.67 | 0.007 |
| | 4 | 0.83 | 0.009 |
| | 5 | 0.98 | 0.010 |
| | 6 | 1.17 | 0.008 |
| | 7 | 1.36 | 0.010 |
| | 8 | 1.51 | 0.012 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 7.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Southeast region. This summary includes 14,381 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.12 | 0.002 |
| | 2 | 0.39 | 0.005 |
| | 3 | 0.53 | 0.007 |
| | 4 | 0.63 | 0.010 |
| | 5 | 0.67 | 0.010 |
| | 6 | 0.74 | 0.007 |
| | 7 | 0.80 | 0.008 |
| | 8 | 0.86 | 0.009 |
| Softwood | 1 | 0.01 | - |
| | 2 | 0.06 | 0.002 |
| | 3 | 0.13 | 0.004 |
| | 4 | 0.23 | 0.006 |
| | 5 | 0.35 | 0.008 |
| | 6 | 0.50 | 0.009 |
| | 7 | 0.65 | 0.012 |
| | 8 | 0.75 | 0.013 |
| All[c] | 1 | 0.13 | 0.002 |
| | 2 | 0.46 | 0.005 |
| | 3 | 0.65 | 0.008 |
| | 4 | 0.86 | 0.011 |
| | 5 | 1.02 | 0.012 |
| | 6 | 1.24 | 0.010 |
| | 7 | 1.45 | 0.013 |
| | 8 | 1.60 | 0.014 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 8.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Great Plains region. This summary includes 2,493 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.06 | 0.002 |
| | 2 | 0.20 | 0.008 |
| | 3 | 0.33 | 0.014 |
| | 4 | 0.51 | 0.023 |
| | 5 | 0.59 | 0.022 |
| | 6 | 0.77 | 0.019 |
| | 7 | 0.88 | 0.021 |
| | 8 | 0.96 | 0.025 |
| Softwood | 1 | 0.01 | 0.001 |
| | 2 | 0.03 | 0.003 |
| | 3 | 0.06 | 0.005 |
| | 4 | 0.10 | 0.008 |
| | 5 | 0.11 | 0.008 |
| | 6 | 0.13 | 0.007 |
| | 7 | 0.16 | 0.009 |
| | 8 | 0.19 | 0.011 |
| All[c] | 1 | 0.06 | 0.003 |
| | 2 | 0.23 | 0.008 |
| | 3 | 0.39 | 0.015 |
| | 4 | 0.61 | 0.025 |
| | 5 | 0.71 | 0.024 |
| | 6 | 0.90 | 0.020 |
| | 7 | 1.04 | 0.022 |
| | 8 | 1.15 | 0.026 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 9.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Rocky Mountain–North region. This summary includes 5,936 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | - | - |
| | 2 | 0.01 | 0.002 |
| | 3 | 0.02 | 0.002 |
| | 4 | 0.02 | 0.003 |
| | 5 | 0.02 | 0.003 |
| | 6 | 0.03 | 0.003 |
| | 7 | 0.03 | 0.003 |
| | 8 | 0.03 | 0.003 |
| Softwood | 1 | 0.05 | 0.001 |
| | 2 | 0.20 | 0.005 |
| | 3 | 0.35 | 0.008 |
| | 4 | 0.51 | 0.013 |
| | 5 | 0.67 | 0.014 |
| | 6 | 0.86 | 0.014 |
| | 7 | 1.04 | 0.016 |
| | 8 | 1.18 | 0.018 |
| All[c] | 1 | 0.05 | 0.001 |
| | 2 | 0.22 | 0.005 |
| | 3 | 0.37 | 0.008 |
| | 4 | 0.53 | 0.013 |
| | 5 | 0.70 | 0.014 |
| | 6 | 0.89 | 0.014 |
| | 7 | 1.07 | 0.016 |
| | 8 | 1.21 | 0.018 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 10.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Rocky Mountain–South region. This summary includes 3,690 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.01 | 0.001 |
| | 2 | 0.05 | 0.004 |
| | 3 | 0.08 | 0.005 |
| | 4 | 0.14 | 0.009 |
| | 5 | 0.18 | 0.010 |
| | 6 | 0.25 | 0.012 |
| | 7 | 0.31 | 0.014 |
| | 8 | 0.36 | 0.016 |
| Softwood | 1 | 0.03 | 0.001 |
| | 2 | 0.15 | 0.005 |
| | 3 | 0.29 | 0.009 |
| | 4 | 0.45 | 0.015 |
| | 5 | 0.59 | 0.017 |
| | 6 | 0.75 | 0.016 |
| | 7 | 0.92 | 0.018 |
| | 8 | 1.04 | 0.019 |
| All[1] | 1 | 0.05 | 0.002 |
| | 2 | 0.21 | 0.006 |
| | 3 | 0.38 | 0.010 |
| | 4 | 0.59 | 0.017 |
| | 5 | 0.77 | 0.019 |
| | 6 | 1.00 | 0.018 |
| | 7 | 1.23 | 0.021 |
| | 8 | 1.40 | 0.023 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 11.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Pacific Northwest–East region. This summary includes 6,964 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | - | - |
| | 2 | 0.01 | 0.001 |
| | 3 | 0.01 | 0.002 |
| | 4 | 0.01 | 0.003 |
| | 5 | 0.02 | 0.003 |
| | 6 | 0.02 | 0.003 |
| | 7 | 0.02 | 0.003 |
| | 8 | 0.02 | 0.002 |
| Softwood | 1 | 0.05 | 0.001 |
| | 2 | 0.19 | 0.005 |
| | 3 | 0.29 | 0.007 |
| | 4 | 0.39 | 0.010 |
| | 5 | 0.51 | 0.011 |
| | 6 | 0.62 | 0.009 |
| | 7 | 0.76 | 0.012 |
| | 8 | 0.87 | 0.013 |
| All[c] | 1 | 0.05 | 0.001 |
| | 2 | 0.19 | 0.005 |
| | 3 | 0.30 | 0.007 |
| | 4 | 0.40 | 0.010 |
| | 5 | 0.53 | 0.011 |
| | 6 | 0.64 | 0.010 |
| | 7 | 0.78 | 0.012 |
| | 8 | 0.89 | 0.013 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 12.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Pacific Northwest–West region. This summary includes 6,478 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.01 | 0.001 |
| | 2 | 0.05 | 0.003 |
| | 3 | 0.08 | 0.005 |
| | 4 | 0.13 | 0.008 |
| | 5 | 0.17 | 0.008 |
| | 6 | 0.21 | 0.007 |
| | 7 | 0.25 | 0.009 |
| | 8 | 0.28 | 0.010 |
| Softwood | 1 | 0.03 | 0.001 |
| | 2 | 0.13 | 0.003 |
| | 3 | 0.23 | 0.006 |
| | 4 | 0.36 | 0.010 |
| | 5 | 0.50 | 0.012 |
| | 6 | 0.67 | 0.011 |
| | 7 | 0.86 | 0.014 |
| | 8 | 1.06 | 0.017 |
| All[c] | 1 | 0.04 | 0.001 |
| | 2 | 0.18 | 0.005 |
| | 3 | 0.32 | 0.008 |
| | 4 | 0.49 | 0.013 |
| | 5 | 0.67 | 0.014 |
| | 6 | 0.88 | 0.013 |
| | 7 | 1.11 | 0.016 |
| | 8 | 1.35 | 0.019 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 13.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Pacific Southwest region. This summary includes 4,629 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.04 | 0.002 |
| | 2 | 0.12 | 0.006 |
| | 3 | 0.19 | 0.010 |
| | 4 | 0.27 | 0.015 |
| | 5 | 0.33 | 0.014 |
| | 6 | 0.48 | 0.015 |
| | 7 | 0.55 | 0.017 |
| | 8 | 0.60 | 0.018 |
| Softwood | 1 | 0.02 | 0.001 |
| | 2 | 0.07 | 0.003 |
| | 3 | 0.13 | 0.005 |
| | 4 | 0.20 | 0.008 |
| | 5 | 0.26 | 0.009 |
| | 6 | 0.35 | 0.008 |
| | 7 | 0.43 | 0.010 |
| | 8 | 0.51 | 0.012 |
| All[a] | 1 | 0.05 | 0.002 |
| | 2 | 0.19 | 0.007 |
| | 3 | 0.32 | 0.011 |
| | 4 | 0.47 | 0.017 |
| | 5 | 0.59 | 0.017 |
| | 6 | 0.83 | 0.016 |
| | 7 | 0.98 | 0.019 |
| | 8 | 1.11 | 0.020 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 14.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Coastal Alaska region. This summary includes 1,830 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac)[a] | SEM (t/ac)[b] |
|---|---|---|---|
| Hardwood | 1 | 0.005 | 0.001 |
| | 2 | 0.02 | 0.003 |
| | 3 | 0.02 | 0.004 |
| | 4 | 0.03 | 0.006 |
| | 5 | 0.06 | 0.010 |
| | 6 | 0.06 | 0.007 |
| | 7 | 0.07 | 0.009 |
| | 8 | 0.09 | 0.010 |
| Softwood | 1 | 0.06 | 0.003 |
| | 2 | 0.26 | 0.011 |
| | 3 | 0.42 | 0.017 |
| | 4 | 0.56 | 0.024 |
| | 5 | 0.64 | 0.022 |
| | 6 | 0.80 | 0.018 |
| | 7 | 0.92 | 0.021 |
| | 8 | 1.03 | 0.026 |
| All[c] | 1 | 0.07 | 0.003 |
| | 2 | 0.28 | 0.012 |
| | 3 | 0.44 | 0.018 |
| | 4 | 0.59 | 0.024 |
| | 5 | 0.70 | 0.024 |
| | 6 | 0.86 | 0.019 |
| | 7 | 0.99 | 0.023 |
| | 8 | 1.12 | 0.027 |

[a] Mean carbon stock values less than 0.005 tons/ac are not reported.

[b] SEM values less than 0.0005 tons/ac are not reported.

[c] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

## APPENDIX 2

Carbon stock estimates by diameter class for Pacific Southwest region examples corresponding to Figure 4.

**Table 15.—Mean and standard error (SEM) of live aboveground carbon AGC stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Pacific Southwest region, western oak. This summary includes 1,181 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac) | SEM (t/ac) |
|---|---|---|---|
| Hardwood | 1 | 0.05 | 0.005 |
| | 2 | 0.21 | 0.017 |
| | 3 | 0.37 | 0.028 |
| | 4 | 0.58 | 0.044 |
| | 5 | 0.70 | 0.041 |
| | 6 | 1.01 | 0.039 |
| | 7 | 1.17 | 0.044 |
| | 8 | 1.27 | 0.048 |
| Softwood | 1 | 0.01 | 0.001 |
| | 2 | 0.02 | 0.003 |
| | 3 | 0.04 | 0.005 |
| | 4 | 0.06 | 0.008 |
| | 5 | 0.07 | 0.008 |
| | 6 | 0.11 | 0.009 |
| | 7 | 0.11 | 0.009 |
| | 8 | 0.13 | 0.010 |
| All[a] | 1 | 0.06 | 0.005 |
| | 2 | 0.23 | 0.017 |
| | 3 | 0.41 | 0.029 |
| | 4 | 0.64 | 0.045 |
| | 5 | 0.77 | 0.041 |
| | 6 | 1.11 | 0.040 |
| | 7 | 1.28 | 0.045 |
| | 8 | 1.40 | 0.049 |

[a] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 16.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Pacific Southwest region, California mixed conifer. This summary includes 1,261 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac) | SEM (t/ac) |
|---|---|---|---|
| Hardwood | 1 | 0.02 | 0.002 |
| | 2 | 0.05 | 0.005 |
| | 3 | 0.08 | 0.009 |
| | 4 | 0.09 | 0.013 |
| | 5 | 0.12 | 0.013 |
| | 6 | 0.16 | 0.011 |
| | 7 | 0.20 | 0.014 |
| | 8 | 0.21 | 0.016 |
| Softwood | 1 | 0.02 | 0.001 |
| | 2 | 0.11 | 0.006 |
| | 3 | 0.20 | 0.011 |
| | 4 | 0.32 | 0.019 |
| | 5 | 0.38 | 0.019 |
| | 6 | 0.51 | 0.015 |
| | 7 | 0.62 | 0.019 |
| | 8 | 0.78 | 0.024 |
| All[a] | 1 | 0.04 | 0.003 |
| | 2 | 0.16 | 0.008 |
| | 3 | 0.29 | 0.015 |
| | 4 | 0.41 | 0.022 |
| | 6 | 0.50 | 0.023 |
| | 5 | 0.67 | 0.019 |
| | 7 | 0.82 | 0.024 |
| | 8 | 1.00 | 0.029 |

[a] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

# APPENDIX 3

Carbon stock estimates by diameter class for forest type examples corresponding to Figure 5.

**Table 17.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Northeast region, spruce-fir forest-type group. This summary includes 1,309 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac) | SEM (t/ac) |
|---|---|---|---|
| Hardwood | 1 | 0.07 | 0.004 |
| | 2 | 0.26 | 0.013 |
| | 3 | 0.33 | 0.019 |
| | 4 | 0.34 | 0.023 |
| | 5 | 0.34 | 0.021 |
| | 6 | 0.39 | 0.015 |
| | 7 | 0.38 | 0.016 |
| | 8 | 0.38 | 0.018 |
| Softwood | 1 | 0.32 | 0.012 |
| | 2 | 1.16 | 0.037 |
| | 3 | 1.48 | 0.048 |
| | 4 | 1.68 | 0.054 |
| | 5 | 1.68 | 0.048 |
| | 6 | 1.65 | 0.037 |
| | 7 | 1.53 | 0.035 |
| | 8 | 1.40 | 0.035 |
| All[a] | 1 | 0.40 | 0.013 |
| | 2 | 1.41 | 0.040 |
| | 3 | 1.81 | 0.053 |
| | 4 | 2.02 | 0.060 |
| | 5 | 2.02 | 0.054 |
| | 6 | 2.04 | 0.041 |
| | 7 | 1.90 | 0.040 |
| | 8 | 1.78 | 0.042 |

[a] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 18.—Mean and standard error (SEM) of live aboveground carbon stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Southeast region, loblolly-shortleaf pine forest-type group. This summary includes 3,933 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac) | SEM (t/ac) |
|---|---|---|---|
| Hardwood | 1 | 0.13 | 0.003 |
| | 2 | 0.39 | 0.008 |
| | 3 | 0.44 | 0.012 |
| | 4 | 0.45 | 0.015 |
| | 5 | 0.39 | 0.013 |
| | 6 | 0.40 | 0.009 |
| | 7 | 0.37 | 0.010 |
| | 8 | 0.35 | 0.011 |
| Softwood | 1 | 0.02 | 0.001 |
| | 2 | 0.13 | 0.006 |
| | 3 | 0.27 | 0.010 |
| | 4 | 0.48 | 0.016 |
| | 5 | 0.72 | 0.021 |
| | 6 | 1.05 | 0.023 |
| | 7 | 1.43 | 0.031 |
| | 8 | 1.71 | 0.035 |
| All[a] | 1 | 0.15 | 0.003 |
| | 2 | 0.52 | 0.010 |
| | 3 | 0.71 | 0.015 |
| | 4 | 0.92 | 0.021 |
| | 5 | 1.11 | 0.023 |
| | 6 | 1.45 | 0.024 |
| | 7 | 1.79 | 0.031 |
| | 8 | 2.06 | 0.035 |

[a]Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 19.—Mean and standard error (SEM) of live aboveground carbon stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Rocky Mountain–South region, aspen-birch forest-type group. This summary includes 861 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac) | SEM (t/ac) |
|---|---|---|---|
| Hardwood | 1 | 0.05 | 0.005 |
| | 2 | 0.20 | 0.015 |
| | 3 | 0.31 | 0.022 |
| | 4 | 0.53 | 0.038 |
| | 5 | 0.67 | 0.041 |
| | 6 | 0.90 | 0.045 |
| | 7 | 1.17 | 0.053 |
| | 8 | 1.36 | 0.061 |
| Softwood | 1 | 0.01 | 0.001 |
| | 2 | 0.05 | 0.004 |
| | 3 | 0.09 | 0.009 |
| | 4 | 0.14 | 0.014 |
| | 5 | 0.18 | 0.015 |
| | 6 | 0.24 | 0.014 |
| | 7 | 0.28 | 0.016 |
| | 8 | 0.31 | 0.018 |
| All[a] | 1 | 0.06 | 0.005 |
| | 2 | 0.24 | 0.016 |
| | 3 | 0.41 | 0.024 |
| | 4 | 0.67 | 0.041 |
| | 5 | 0.86 | 0.045 |
| | 6 | 1.14 | 0.048 |
| | 7 | 1.45 | 0.057 |
| | 8 | 1.67 | 0.064 |

[a] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

**Table 20.—Mean and standard error (SEM) of live aboveground carbon (AGC) stock estimates by diameter class for hardwood stems, softwood stems, and all stems, Pacific Northwest–West region, Douglas-fir forest-type group. This summary includes 3,740 plots.**

| Species group | Diameter class (d.b.h. inches) | Mean AGC stock (t/ac) | SEM (t/ac) |
|---|---|---|---|
| Hardwood | 1 | 0.01 | 0.001 |
| | 2 | 0.04 | 0.003 |
| | 3 | 0.06 | 0.005 |
| | 4 | 0.09 | 0.007 |
| | 5 | 0.13 | 0.008 |
| | 6 | 0.16 | 0.006 |
| | 7 | 0.18 | 0.007 |
| | 8 | 0.19 | 0.008 |
| Softwood | 1 | 0.02 | 0.001 |
| | 2 | 0.11 | 0.004 |
| | 3 | 0.20 | 0.008 |
| | 4 | 0.33 | 0.013 |
| | 5 | 0.47 | 0.015 |
| | 6 | 0.69 | 0.016 |
| | 7 | 0.91 | 0.019 |
| | 8 | 1.18 | 0.025 |
| All[a] | 1 | 0.03 | 0.001 |
| | 2 | 0.14 | 0.005 |
| | 3 | 0.26 | 0.009 |
| | 4 | 0.42 | 0.015 |
| | 5 | 0.60 | 0.017 |
| | 6 | 0.84 | 0.017 |
| | 7 | 1.09 | 0.021 |
| | 8 | 1.37 | 0.026 |

[a] Note that the sum of the hardwood and softwood stem values may not equal the total stem value due to rounding.

Hoover, Coeli M.; Smith, James E. 2020. **Selecting a minimum diameter for forest biomass and carbon estimation: How low should you go?** General Technical Report NRS-196. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 32 p. https://doi.org/10.2737/NRS-GTR-196.

Forest inventories are traditionally designed to produce estimates of merchantable timber volume but are increasingly used to estimate stand-level biomass or carbon. Since inventory is volume-focused, it is common practice to tally stems 5 inches and greater in diameter (at breast height; d.b.h.). When estimating carbon or biomass, practitioners may be concerned about the effect of omitting smaller stems from the inventory. We present summaries to provide indicators of when smaller diameters may be less important for an accurate estimate to assist those foresters considering adding carbon estimates to traditional inventory objectives. Small stems (e.g., 2 or 3 inches d.b.h.) may contribute appreciable biomass within a few specific types of forest stands, such as for spruce-fir or lodgepole pine, but generally the contribution is minor. Similarly, the 5- or 6-inch stems, which are moderately large for some stands, will contribute very little to stand biomass for some forest types, particularly in western forests (e.g., Douglas-fir and ponderosa pine). These are well known patterns, and we suggest such information be used to inform the choice of minimum tally diameter. Pragmatic threshold values vary by region because the importance of smaller stems is not fixed at a single diameter over all U.S. forests.

KEY WORDS: tally tree diameter, forest inventory, forest-type group

Northern Research Station

www.nrs.fs.fed.us