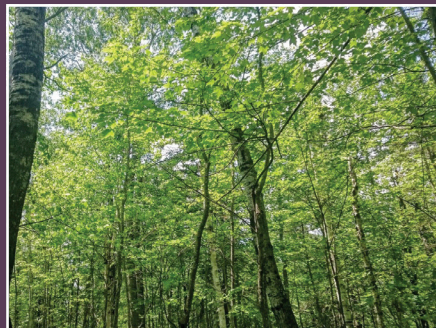
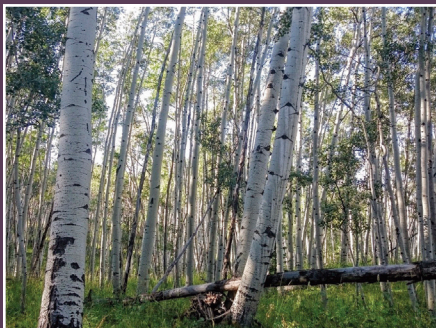




United States Department of Agriculture

A Cost-Effective Field Measurement Protocol to Support Lidar-Assisted Carbon Monitoring Programs—Implementing A Prototype Design at Six Different Sites in the United States

Kate Legner, Hans-Erik Andersen, Andrew Cooke, and Warren Cohen



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Cover (clockwise from upper left): Study areas in Colorado, Maine, Minnesota, New Jersey, Oregon, and South Carolina. Photos by Michael Hicks.

Abstract

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A cost-effective field measurement protocol to support lidar-assisted carbon monitoring programs—implementing a prototype design at six different sites in the United States. Gen. Tech. Rep. PNW-GTR-984. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 66 p.

Given the increasing interest in the use of lidar-based remote sensing to support carbon monitoring systems, including those used for measurement, reporting, and verification requirements for REDD+ (reduced emissions from deforestation and degradation) programs in tropical nations, there is a corresponding need for the cost-effective field measurement systems to enable model development and robust assessment of uncertainty in these programs. In this report, we describe an efficient field sampling design and measurement protocol designed to provide field-based estimates of biomass/carbon stored in trees and coarse woody materials to support complex, multilevel carbon monitoring systems using Landsat time series and airborne lidar. Airborne lidar data were collected as a strip sample (single flight lines spaced 5 km apart) at six sites in the United States (Colorado, Maine, Minnesota, Oregon, Pennsylvania/New Jersey, and South Carolina) (298 total flight lines), and about 50 field plots were established within the lidar coverage at each site. Field plots were distributed across 15 (3 cover $\times$ 5 height) strata at each site, using field protocols that were consistent with those of the U.S. Department of Agriculture Forest Service Forest Inventory and Analysis program. Field measurements were collected digitally on personal tablets and uploaded daily into a database. Preliminary regression analyses indicate strong relationships between lidar metrics and tree biomass at all sites.

Keywords: Forest inventory, forest biomass, REDD+, carbon monitoring, field sampling design, airborne lidar, lidar sampling.

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Introduction

General Motivation

There is increasing interest globally in the development of carbon monitoring systems that can make efficient use of emerging, state-of-the-art remote sensing technologies and spatial analysis techniques to increase precision and reduce costs. In many countries, national greenhouse gas inventory reporting to the UN Framework Convention on Climate Change (UNFCCC) is often currently based on relatively expensive, permanent field plot networks, such as national forest inventory systems, augmented with available remotely sensed imagery. These systems, however, are either not universally available (such as in developing countries) or—as in the United States—lack the consistency necessary to accurately estimate carbon stocks back to a 1990 baseline as required by the UNFCCC. Through a grant provided by the National Aeronautics and Space Administration Carbon Monitoring System (CMS) program, a team of researchers led by Warren Cohen, U.S. Department of Agriculture (USDA), Forest Service, Pacific Northwest Research Station, developed a prototype “measurable, reportable, verifiable” (MRV) design for cost-effective carbon monitoring using a limited number of field plots, lidar sampling, and disturbance information derived from Landsat time series data. Airborne laser scanning provides highly detailed, accurate measurements of forest canopy structure and when collected in a sampling mode (i.e., a strip sample) can be a cost-effective component of a large-area forest carbon inventory (McRoberts et al. 2014, Næsset et al. 2013). In this study, high-density airborne lidar data were collected in a sampling mode over five sites (each about 21 000 km² in area) distributed throughout the United States (fig. 1), with lidar collected in single swaths (flight lines) oriented north to south and spaced 5 km apart (fig. 2). These sites were previously selected for the Landscape Change Monitoring System (USDA FS 2019). An important additional objective of this study was to develop an efficient field sampling design that would support the development of robust predictive models for estimating forest biomass using a combination of remote sensing data sources.¹ Given the high cost of field sampling compared to remote sensing, the field sampling design developed in this study used a relatively small number of field plots (about 50 at each site) (each 0.08 ha [0.2 ac] in area—covering approximately the same area as a 30 × 30 m Landsat pixel) that were distributed (via stratified sampling) across the full range of structural conditions (height, cover) observed in the lidar strip sample. In this technical report, we describe in detail how plot locations were selected and how field measurements were collected, along with a summary of the data and preliminary modeling results.

¹ Because carbon weight is generally assumed to be $0.5 \times$ biomass, we focused on estimation of biomass throughout this study.



Figure 1—United States overview map with study areas outlined.

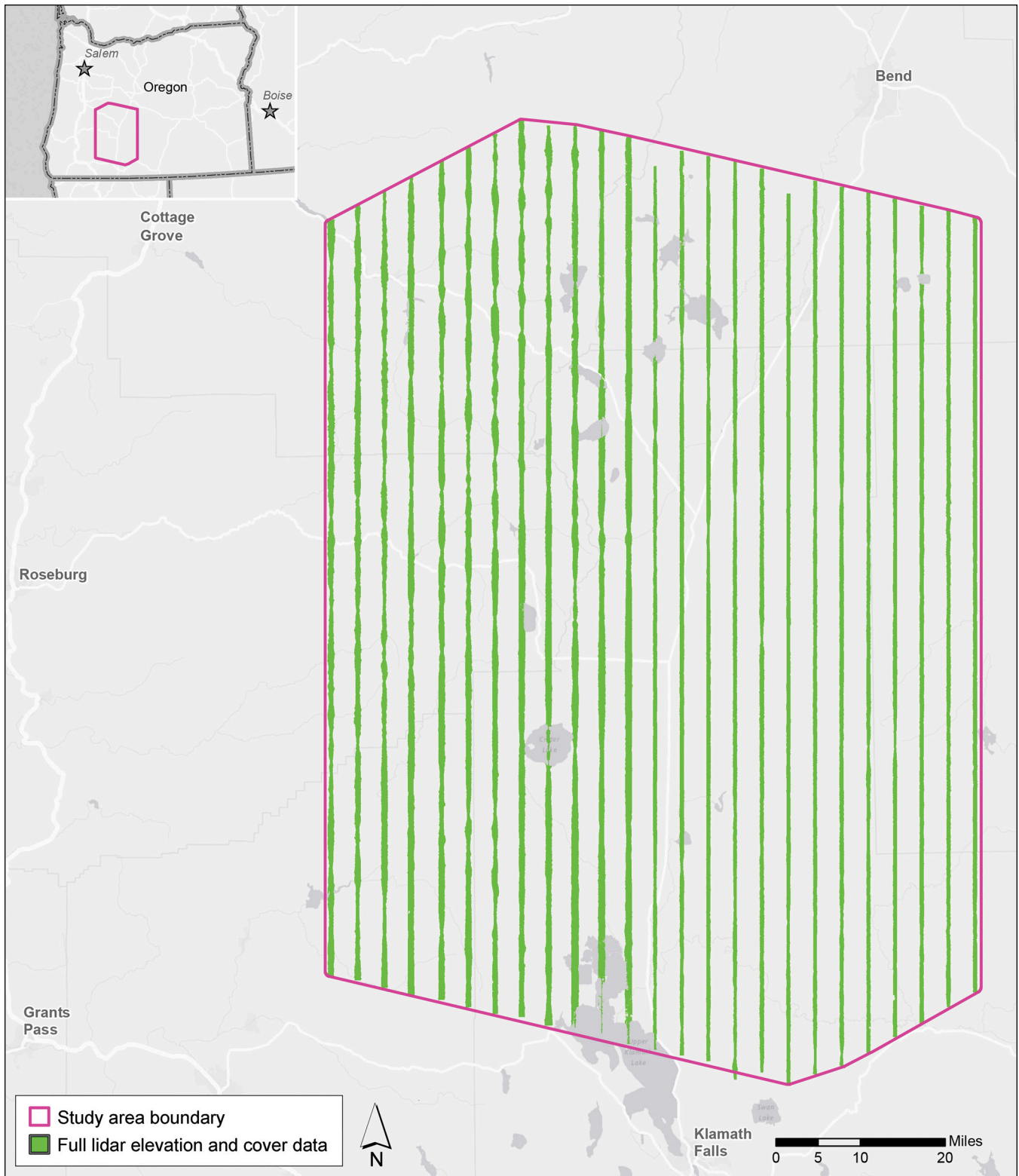


Figure 2—Buffered convex hull around lidar macro boundary. The Oregon study area is pictured here.

Lidar Data Collection

Lidar data were collected using a Riegl® LMS-Q680i system² at five sites (Colorado, Maine, Minnesota, Pennsylvania/New Jersey, and South Carolina) in summer 2014 and at a sixth site (Oregon) in summer 2015. All data were collected during snow-free periods when vegetation was fully leafed out and non-senescent, with specific dates of collection varying by study site depending on elevation, vegetation phenology, and other factors. The data were collected in north-south oriented flight lines spaced 5 km apart. Technical specifications for the lidar acquisition are provided in table 1. The lidar data were processed in the Fusion software package (McGaughey 2015) to produce raster geospatial datasets of various metrics with a 30-m cell size.

Table 1—Lidar acquisition technical specifications

Point density	Altitude (AMT)	Field of view	Pulse rate	Full swath width	Horizontal accuracy (RMSEz)	Vertical accuracy (RMSEz)
<i>Pulses per square meter</i>	<i>Feet</i>	<i>Degrees</i>	<i>Hertz</i>	<i>Meters</i>	<i>Centimeters</i>	<i>Centimeters</i>
4	2,400	60	330,000	812	50	50

Lidar Preprocessing

Removing Water and Developed Areas

Nonforested areas were removed from study areas covered by lidar rasters using the 2011 National Land Cover Database (NLCD) (Homer et al. 2015). To use the NLCD 2011 dataset with the project lidar data, it was first projected into the Universal Transverse Mercator (UTM) coordinate system in the UTM zone associated with each site location. Currently, NLCD 2011 data are delivered in a U.S. Geological Survey (USGS) Albers equal-area conic projection that uses the North American Datum of 1983 (NAD83) and meters as the linear unit. Lidar data are provided in various UTM projections (table 2) by using the National Spatial Reference System NAD83 2011 revision, and meters as the linear unit. Both datasets have a 30-m cell size. The NLCD 2011 data were clipped to each site for quicker processing and more accurate projection.

A convex hull was built around the lidar flight lines (macro boundary) to define the full study area for each site. This convex hull was buffered by an additional

² The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 2—Projections used for each study area

Site	Projection	Reference ID
Colorado	NAD83 NSRS2011 UTM ZONE 13 N	EPSG:6342
Maine	NAD83 NSRS2011 UTM ZONE 19 N	EPSG:6348
Minnesota	NAD83 NSRS2011 UTM ZONE 15 N	EPSG:6344
Oregon	NAD83 NSRS2011 UTM ZONE 10 N	EPSG:6339
Pennsylvania/New Jersey	NAD83 NSRS2011 UTM ZONE 18 N	EPSG:6347
South Carolina	NAD83 NSRS2011 UTM ZONE 17 N	EPSG:6346

kilometer to eliminate edge effects at the ends of the flight lines and along the edges of the two outermost (east and west) flight lines (fig. 2). The NLCD data were clipped to this study area boundary and reprojected using nearest-neighbor resampling into the UTM projection for each site, maintaining the 30-m pixel size. The reprojected pixels were snapped to the lidar datasets so that cell boundaries were aligned between the lidar and the NLCD rasters.

We selected for potentially forested areas within each study area by eliminating all other NLCD land classifications except for forest, shrubland, herbaceous, and wetland (table 3). To do so, the NLCD raster was simplified into a binary raster of areas to use and areas to remove. Forest, shrubland, herbaceous, and wetland land classifications were kept as areas to use, and all other land classifications were removed (figs. 3 and 4).

Table 3—The classification system used by the National Land Cover Database 2011

Class and value	Classification description
Water:	
11 Open water	Areas of open water, generally with <25 percent cover of vegetation or soil.
12 Perennial ice/snow	Areas characterized by a perennial cover of ice or snow, generally >25 percent of total cover.
Developed:	
21 Developed, open space	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for <20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
22 Developed, low intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family housing units.
23 Developed, medium intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 to 79 percent of the total cover. These areas most commonly include single-family housing units.
24 Developed high intensity	Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses, and commercial/industrial zones. Impervious surfaces account for 80 to 100 percent of the total cover.

Table 3—The classification system used by the National Land Cover Database 2011 (continued)

Class and value	Classification description
Barren:	
31 Barren land (rock/sand/clay)	Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for <15 percent of total cover.
Forest:	
41 Deciduous forest	Areas dominated by trees generally >5 m tall, and comprising >20 percent of total vegetation cover; >75 percent of the tree species shed foliage simultaneously in response to seasonal change.
42 Evergreen forest	Areas dominated by trees generally >5 m tall, and comprising >20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.
43 Mixed forest	Areas dominated by trees generally >5 m tall, and >20 percent of total vegetation cover. Neither deciduous nor evergreen species are >75 percent of total tree cover.
Shrubland:	
51 Dwarf scrub	Alaska-only areas dominated by shrubs <20 cm tall with shrub canopy typically >20 percent of total vegetation. This type is often co-associated with grasses, sedges, herbs, and nonvascular vegetation.
52 Shrub/scrub	Areas dominated by shrubs <5 m tall with shrub canopy typically comprising >20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted by environmental conditions.
Herbaceous:	
71 Grassland/herbaceous	Areas dominated by graminoid or herbaceous vegetation, generally comprising >80 percent of total vegetation. These areas are not subject to intensive management such as tilling, but can be used for grazing.
72 Sedge/herbaceous	Alaska-only areas dominated by sedges and forbs, generally comprising >80 percent of total vegetation. This type can occur with significant other grasses or other grass-like plants and includes sedge tundra and sedge tussock tundra.
73 Lichens	Alaska-only areas dominated by fruticose or foliose lichens, generally comprising >80 percent of total vegetation.
74 Moss	Alaska-only areas dominated by mosses, generally comprising >80 percent of total vegetation.
Planted/cultivated:	
81 Pasture/hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for >20 percent of total vegetation.
82 Cultivated crops	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for >20 percent of total vegetation. This class also includes all land being actively tilled.
Wetlands:	
90 Woody wetlands	Areas in which forest or shrubland vegetation accounts for >20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
95 Wetlands	Areas in which perennial herbaceous vegetation accounts for >80 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Source: http://www.mrlc.gov/nlcd11_leg.php.

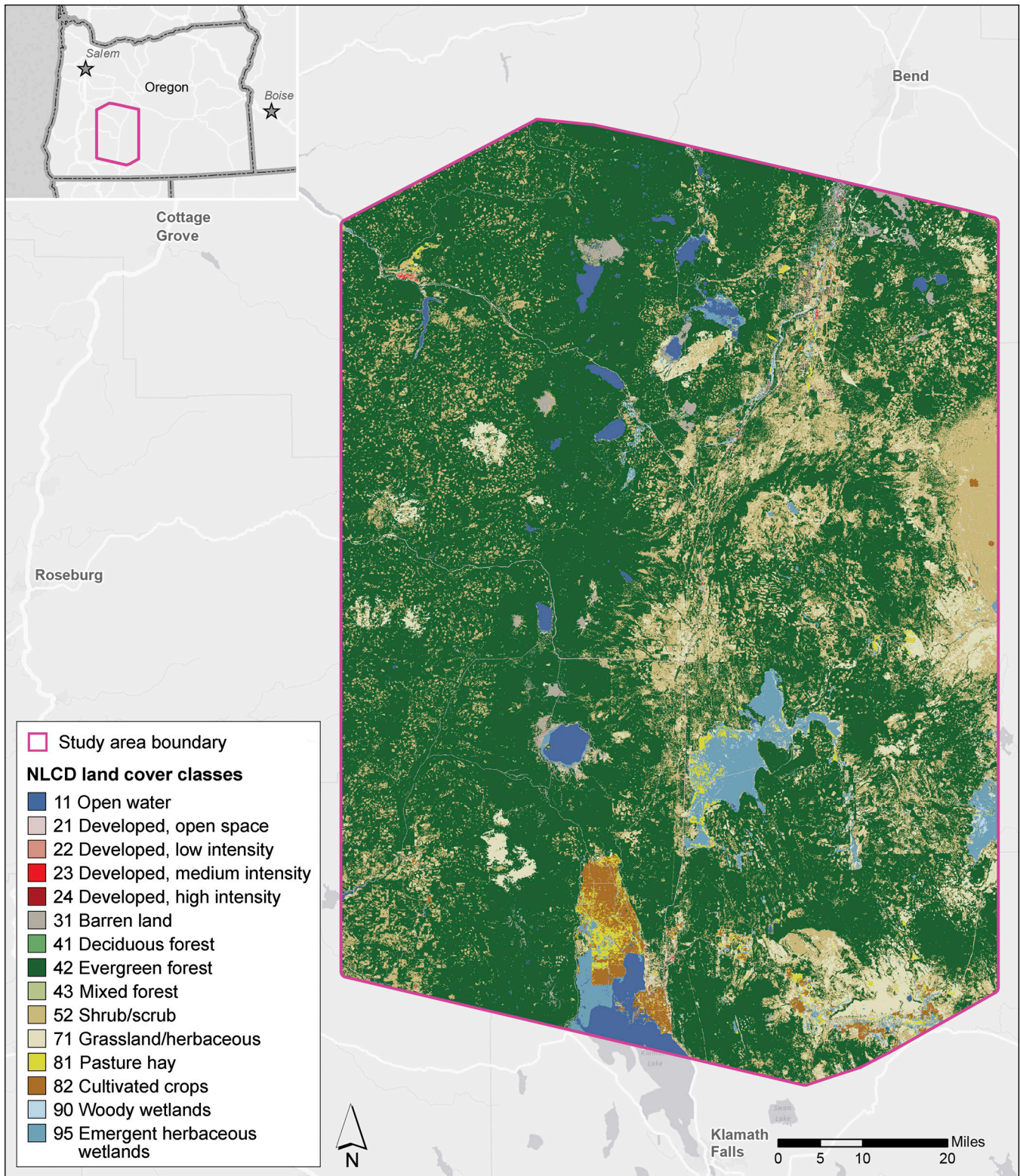


Figure 3—National Land Cover Class (NLCD) 2011 land cover classes clipped to buffered convex hull and projected. The Oregon study area is pictured here.

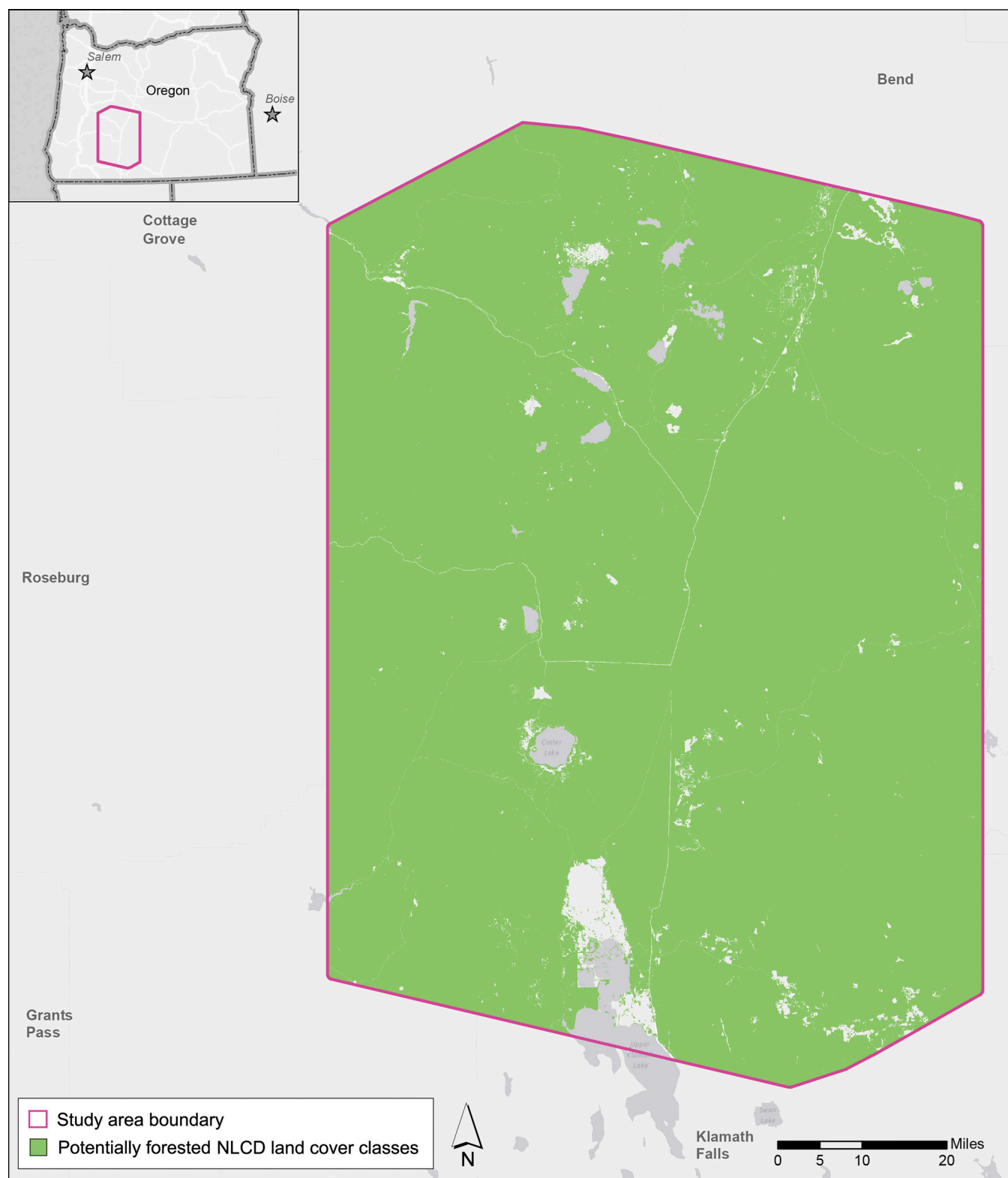


Figure 4—Potentially forested National Land Cover Class (NLCD) land cover classes. The Oregon study area is pictured here.

Removing Lidar Strip Edges

The lidar data were generally collected in single flight lines (strips) with no overlap. Because of topography and changes in aircraft speed and orientation, these strips varied in width, but measured up to 800 m wide. We clipped lidar rasters into 300-m-wide polygons centered on each flight line to standardize strip width, ignored strip edges where there is a high likelihood of missing data, and limited the use of data collected with high off-nadir scan angles. Only plots inside these polygons were used to determine candidate plots.

Removing Areas With Low Percentage of Cover

The lidar metric of percentage of first returns above 1.37 m (PC_{1st}) was used as a proxy for percentage of cover. This metric was used to represent areas where there was cover at breast height. A percentage cover raster was created and used to further remove areas that are unlikely to be forest. To maintain consistency with USDA Forest Service Forest Inventory and Analysis (FIA) definitions of forest, cells with a percentage cover value of 10 or less were removed (USDA FIA 2019).

Defining Lidar Strata

Strata boundaries—

Using lidar data in the design phase of sampling (i.e., as the basis of stratified sampling) has been successfully demonstrated in several previous studies (Gobakken et al. 2013, Hawbacker et al. 2009, Maltamo et al. 2010) in which lidar structural classes were based on a measure of stand height (e.g., 90th percentile height, 70th percentile height, etc.) and canopy density (e.g., percentage of lidar returns above 2 m). Once lidar specifications were met and the nonforest cover classes were removed (based on criteria stated above), 10,000 random cells were selected from the remaining valid cells in each study area (table 4). These sample cells were used to derive the strata boundaries for each study area (fig. 5; app. 1). Fifteen

Table 4—Sample size specifications for each study area

Study area	Valid data cell count	Valid data area	Valid data	Sample cell count	Sample area	Sample	Sample
		<i>Square kilometers</i>	<i>Acres</i>		<i>Square kilometers</i>		
Colorado	712,745	641	158,511	10,000	9	2,224	0.014
Maine	904,147	814	201,078	10,000	9	2,224	0.011
Minnesota	1,020,716	919	227,002	10,000	9	2,224	0.01
Oregon	1,156,292	1,041	257,153	10,000	9	2,224	0.009
Pennsylvania/New Jersey	630,367	567	140,190	10,000	9	2,224	0.016
South Carolina	864,489	778	192,258	10,000	9	2,224	0.012

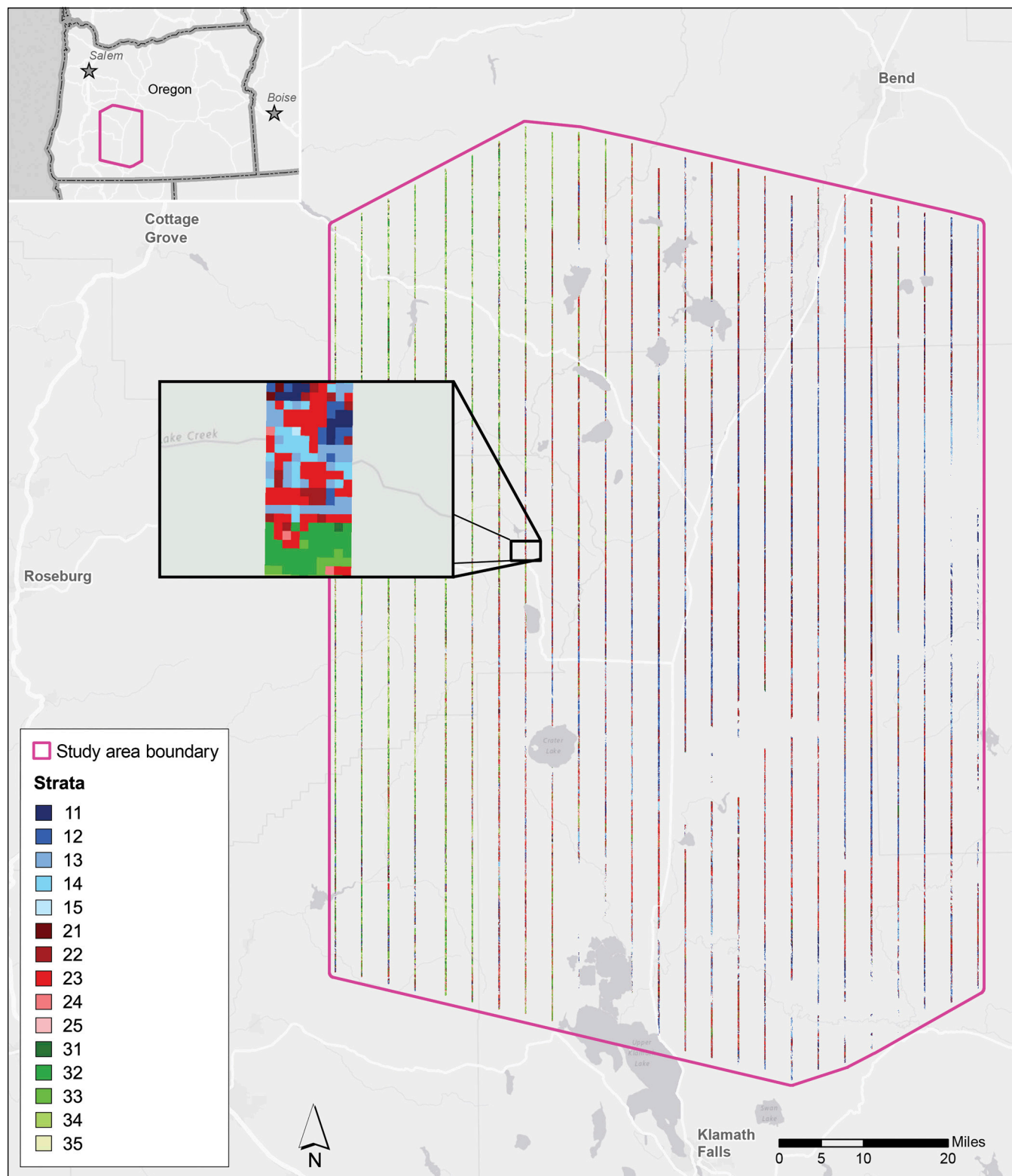


Figure 5—Example distribution of sample lidar height (P90) and cover (PC_{1st}) metrics, divided into strata for the Oregon study area. Strata 11, 21, and 31 had heights extended from the minimum sample height (dashed line) down to the minimum height cutoff of 1.3716 m. Strata 15, 25, and 35 had heights extended from the 99th percentile sample height (dashed line) up to the maximum height cutoff of 70 m.

strata were delineated based upon vegetation cover and height classes within the random cells.

Within a cell, the percentage of cover (PC_{1st}) ranged from 10 to 100 and was divided evenly into three classes: cover classes 1, 2, and 3, which ranged from 10 to 40 percent, 40 to 70 percent, and 70 to 100 percent, respectively. The lidar 90th percentile height metric (Elev.P90) was used to represent tree height. Within each cover class, the P90 height range, from the minimum observed value to the 99th percentile value, was divided evenly into five classes (height classes 1 through 5). The lowest height class was extended down to the minimum height cutoff of 1.37 m (where diameter at breast height was measured), and the highest height class was extended up to the maximum height cutoff for each study area (table 5). Strata were numbered as two-digit numbers using cover class as the first digit and height class as the second digit, resulting in strata numbered from 11 to 15, 21 to 25, and 31 to 35.

The minimum height cutoff was a byproduct of the lidar metrics chosen for this analysis. The maximum height cutoff was determined by rounding up to the nearest meter the 99.99th percentile of the sample P90 heights. For the South Carolina site, this was set manually to 40 m. For the Maine site, this was manually set to 36 m. A maximum height cutoff was used to remove lidar data that was clearly not forest, such as unusually tall electrical transmission towers. Appendix 2 provides the PC_{1st} and P90 boundary values for each stratum by study area.

Table 5—P90 maximum height cutoffs for each study area

Study area	P90 maximum height cutoff
	<i>Meters</i>
Colorado	36
Maine	36
Minnesota	31
Oregon	69
Pennsylvania/New Jersey	47
South Carolina	40

Final cell assignments—

Once strata boundaries were defined for each site, every remaining cell was assigned to a stratum using the PC_{1st} and P90 lidar rasters and the strata ranges (fig. 6). Appendix 3 provides the breakdown of area in each stratum for each study area. NoData cells had missing data in the P90 raster. Stratum 0 cells did not meet the height or cover criteria to be assigned to a bin. Likely these were above the maximum height cutoff.

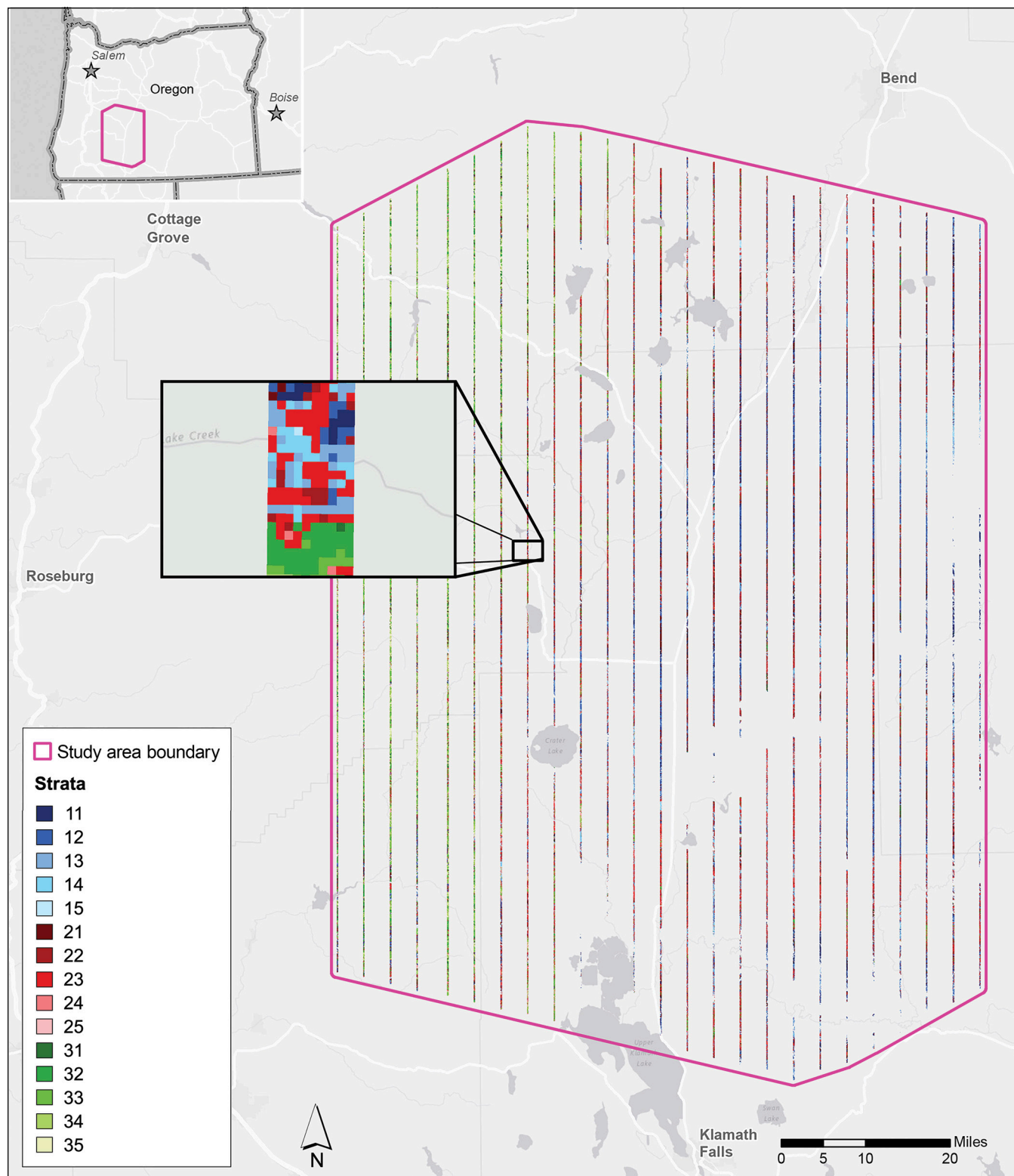


Figure 6—Strata assignment for the full Oregon study area.

Candidate Plot Locations

Across the fifteen strata, a minimum of 23 to 24 candidate plots were generated in each stratum (fig. 7). Each sample plot is represented by a 53-ft fixed-radius circular area. For plot details, see the “Photo Interpretation” and “Plot Establishment” sections below. Candidate plots were evaluated, and potential sample plots to be visited in the field were selected from these candidates based upon accessibility and valid forest land cover status (see “Photo Interpretation” section). Once in the field, crews aimed to visit 50 sample plots at each study area. These 50 plots were distributed across the strata with four plots from strata 11, 15, 23, 31, and 35 (the corners and middle rectangles in fig. 5), and three plots from each of the remaining 10 strata. An example of the distribution of 50 sample plots across the Oregon study area can be seen in figure 8.

The total number of candidate plots generated varied by study area (table 6). In the first three study areas visited early in the field season (Maine, Pennsylvania/New Jersey, and South Carolina), 350 candidate plots were randomly selected from the available raster cells in each bin. In the Pennsylvania/New Jersey site, an

Table 6—Number of candidate plots produced in each study area

Stratum	Study area	
	Maine, Pennsylvania/New Jersey, ^a South Carolina	Colorado, Minnesota, Oregon
11	24	50
12	23	50
13	23	50
14	23	50
15	24	50
21	23	23
22	23	23
23	24	24
24	23	23
25	23	23
31	24	24
32	23	23
33	23	23
34	23	23
35	24	24
Total	350	483

Note: Strata are numbered using cover class as the first digit and height class as the second digit. Increasing values indicate a higher percentage of cover and greater tree height.

^a 1,775 additional candidate plots were produced in Pennsylvania/New Jersey.

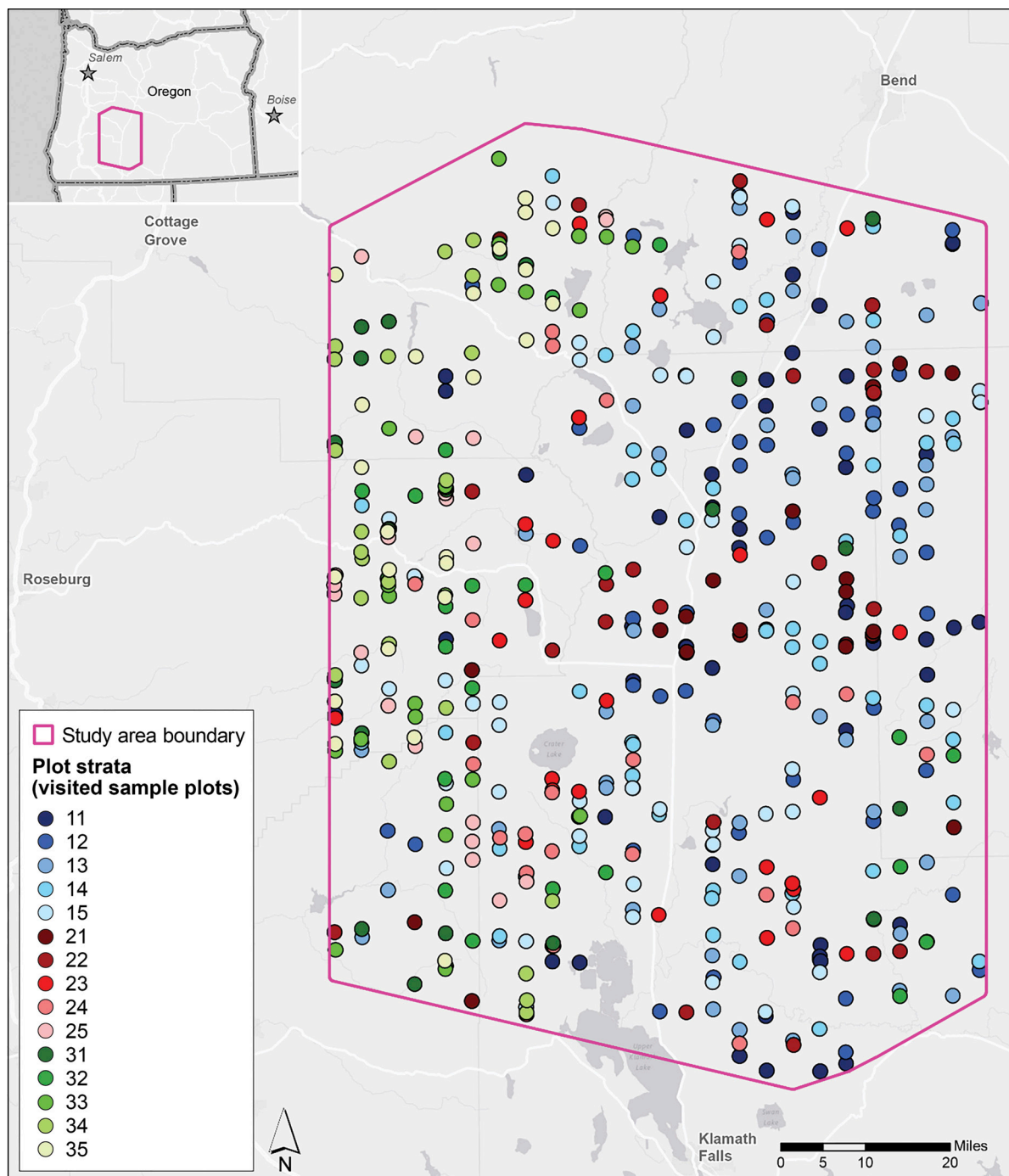


Figure 7—Final Oregon candidate plot locations colored by strata.

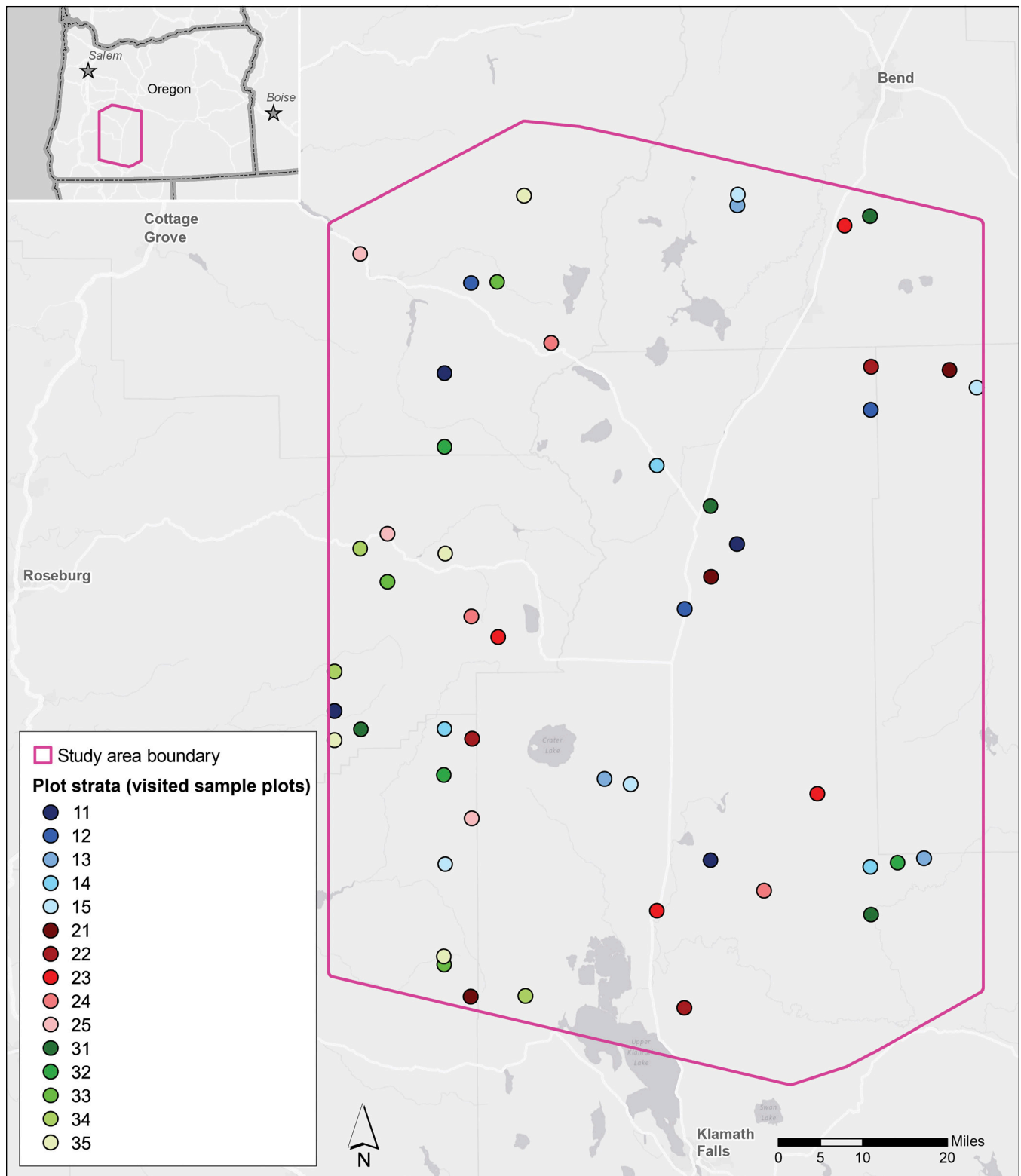


Figure 8—Final Oregon sample plots where field data were collected.

additional 1,775 candidate plots across all strata were generated to create enough forested sample plots. These additional candidates were added because in photo interpretation (see details in “Photo Interpretation” section) many candidate plots on private land and in developed areas were seen to contain nonforested land such as backyards, industrial areas, agricultural areas, and other developed features. This resulted in only two to three candidate plots remaining as potential sample plots after photo interpretation, especially in cover class 1 strata 11 through 15. For the remaining study areas (Colorado, Minnesota, and Oregon), 483 candidate plots were produced, with the additional candidate plots in cover class 1 strata. However, all efforts were made to sample from the first 23 to 24 generated candidate plots to mirror the candidate plots in the first three study areas sampled.

Photo Interpretation

All candidate plots in each study area were evaluated using photo interpretation to determine (1) the current land cover status of each plot, and (2) whether crews would be able to safely access and take measurements at each plot.

Because some study areas were dominated by actively managed forests and logging (Maine and South Carolina) or have relatively high population density and are dominated by private land ownership (Pennsylvania/New Jersey and South Carolina), land cover status in these regions was subject to more rapid change, and recent imagery was needed for adequate determination of land cover status. To obtain the most recent and accurate representation of current land cover status, we used Google Earth™ imagery. Dates of imagery varied between and within our study areas (table 7). Only with older imagery (19 May 2012) in Pennsylvania/ New Jersey did we encounter a change in present land cover status from forested to developed areas once sites were visited on the ground. Google Earth imagery was also easily accessible and at a high enough spatial resolution to determine current land cover status.

Table 7—Dates of Google Earth™ imagery used for each study area

Study area	Earliest imagery	Latest imagery
Colorado	9 April 2013	3 April 2015
Maine	9 April 2013	17 September 2013
Minnesota	9 April 2013	9 April 2013
Oregon	9 April 2013	9 April 2013
Pennsylvania/ New Jersey	7 October 2011	11 November 2014
South Carolina	9 April 2013	7 March 2015

Similarly to methods used by the FIA program, we aimed to sample only forested and accessible candidate plots. We determined land cover status and excluded plots by using several FIA nonforest condition nonsampled reasons (USDA FIA 2019). The following is a list of these exclusion criteria:

Criterion

Outside U.S. boundary
Denied access area
Hazardous situation
Agricultural land
 Cropland
 Improved pasture (graded or mowed)
 Idle farmland
 Orchard
 Christmas tree plantation
 Maintained wildlife opening
 Windbreak/shelterbelt
Rangeland (grass/forb/shrubland)
Developed land
 Cultural or urban (business, residential, other)
 Rights-of-way
 Recreation
 Mining
Other
 Naturally nonvegetated (barren rock, sand, lava, glaciers, other)
 Vegetated wetland
 Beach
 Nonforest chaparral areas

During lidar preprocessing and stratification, candidate plots were determined to be forested if they had greater than 10 percent forest cover. Although plots with nonforested land cover status, such as developed land, rangeland, or agricultural lands, should have been removed during lidar preprocessing, occasionally some candidate plots fell into these areas or on the boundaries of these areas. For example, in heavily developed areas of Pennsylvania and New Jersey, candidate plots frequently fell on the border between forested and developed land such as backyards (fig. 9). These plots were automatically excluded as potential sample plots.

Plots that contained all-terrain vehicle or dirt bike trails, old skid trails, and old logging roads (if unimproved and unmaintained) were not immediately disqualified from the list of candidate plots (fig. 10) as opposed to improved and maintained roads, which were excluded (fig. 11).



Figure 9—Example of partially forested/partially developed candidate plot frequently encountered in the Pennsylvania/New Jersey study area. Yellow circle denotes 53-ft plot radius.



Figure 10—Example of an unimproved and unmaintained road passing through a candidate plot in New Jersey. Yellow circle denotes 53-ft plot radius.



Figure 11—Example of an improved and maintained road passing through a candidate plot in New Jersey. Yellow circle denotes 53-ft plot radius.

Tree plantations covered significant portions of our study area in South Carolina, and plots with plantation land cover were not immediately excluded (fig. 12).

Additionally, plots that contained portions of waterways such as rivers, lakes, or ponds were excluded from the candidate plot list (fig. 13), but intermittent streams were not. Finally, in Maine, a small portion of the lidar data crossed into Canada, and these plots were automatically subject to exclusion because they fell outside the U.S. border.

Accessibility of each plot was determined through analysis of proximity to roadways, roadway quality, plot topography, and other potential hazards. Field crews were transported by small sport utility vehicles, thus candidate plots were disqualified if they were located more than 2 mi from the nearest drivable roadway. Road quality and status were difficult to determine through imagery alone in study areas with considerable backcountry such as Colorado and Maine. Additionally, at higher elevations in part of the Colorado study area, Google Earth imagery that dated from 3 April 2015 showed the region to be covered in snow, with indeterminable road quality and status, disqualifying several plots from this section of the study area. Frequently, candidate plots were determined to be inaccessible once a crew was already on the ground but could not access the plot because of current road quality or drivability impaired by weather conditions. In areas with



Figure 12— Example of a plot located in a tree plantation, frequently encountered in South Carolina. Yellow circle denotes 53-ft plot radius.



Figure 13— Example a candidate plot containing a wetland and water body in New Jersey. Yellow circle denotes 53-ft plot radius.

extreme topography, such as Colorado and western Oregon, acceptable distance to roadways was decreased if necessary to allow for safe and timely travel to plot. Plots were excluded if they contained visible cliffs or if slopes appeared hazardous either within the plot or along the potential route to the plot (fig. 14). Other hazards that disqualified candidate plots included potentially dangerous water crossings en route to the plot, signs of previous land/rockslides, evidence of heavy windthrow, etc. The final list of selected plots captured a representative range of NLCD vegetation cover classes at each site (table 8).

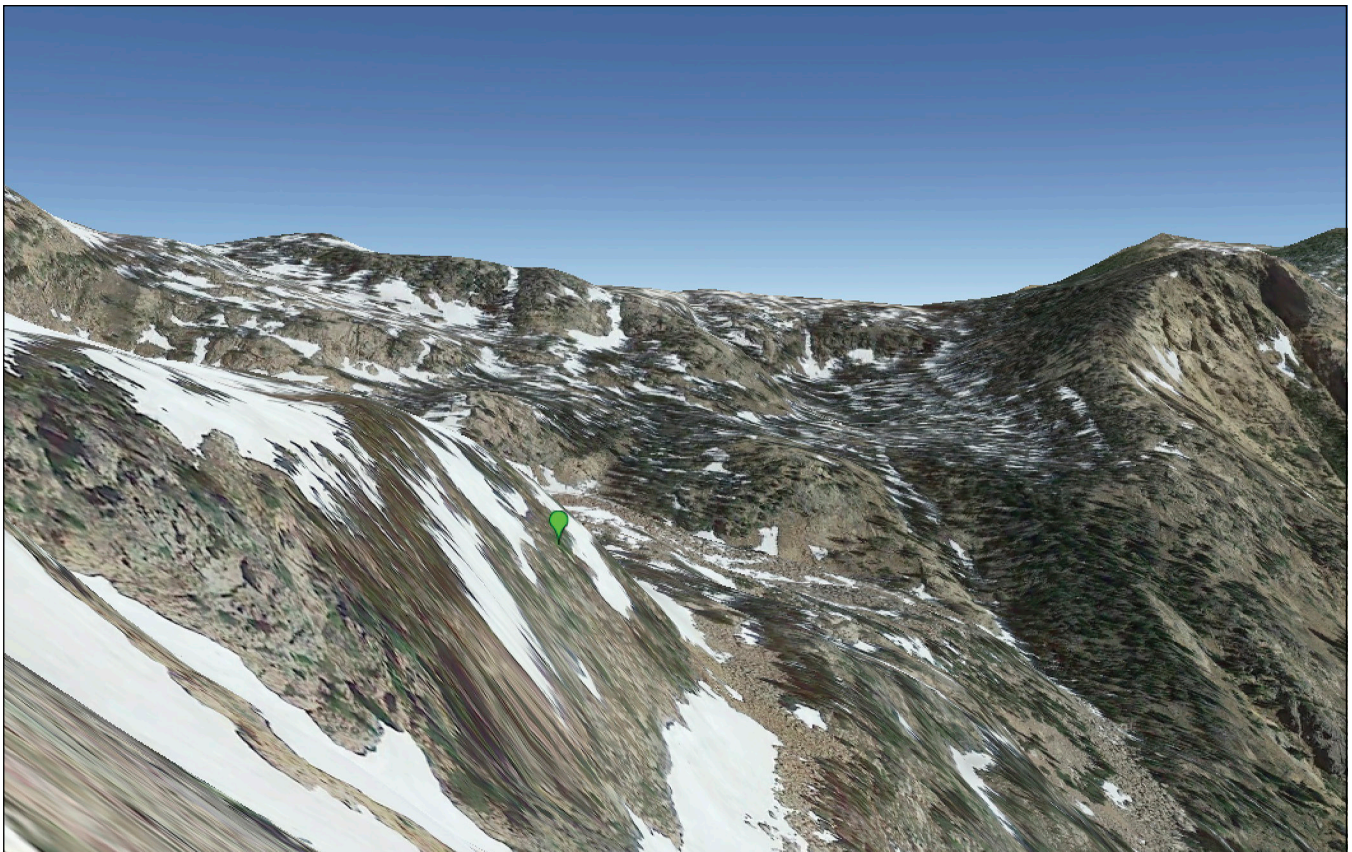


Figure 14—Oblique Google Earth™ image of a hazardous candidate plot location in Colorado.

Table 8—Number of plots classified as a given National Land Cover Database (NLCD) 2011 class within each study area

NLCD class	NLCD code	Study area					
		Colorado	Maine	Minnesota	Oregon	Pennsylvania/ New Jersey	South Carolina
Open water	11		4			3	2
Developed, open space	21		2		1	4	2
Developed, low intensity	22					2	2
Developed, medium intensity	23		1				
Barren land	31					10	1
Deciduous forest	41	16	9	10		5	
Evergreen forest	42	22	10	4	41	3	19
Mixed forest	43	4	11	9		5	
Shrub/scrub	52	2	7	7	7		2
Herbaceous	71	2	1	2	1	3	2
Hay/pasture	81					8	1
Cultivated crops	82					4	
Woody wetlands	90		4	16		3	17
Emergent herbaceous wetlands	95			2		50	2
Total plots visited		46	49	50	50	3	50

Ownership Determination

Once photo interpretation of all candidate plots was complete, remaining plot locations were overlaid with land ownership layers in ArcGIS™ to determine ownership and further assess accessibility. The USGS Protected Area Database (Gergely and McKerrow 2016) provided boundaries of land parcels owned or managed by public agencies or nonprofit organizations. If necessary, we obtained other land ownership information within specific counties by accessing online county land records and parcel data. Google Maps occasionally provided additional ownership information. Frequently, however, parcel data within particular counties were unavailable online. Plots with unavailable ownership information were disqualified temporarily. Once crews were working within a study area, they occasionally attempted to determine ownership of temporarily disqualified plots by talking to local landowners and residents if it became clear that a particular plot was one of the most accessible options within a stratum. After determination of land ownership, we contacted landowners via telephone or e-mail to explain project objectives, request permission to physically access plot locations, and outline field work

timelines. We completed permit applications if requested and worked with landowners to fulfill other requests such as specific plot visitation times, notification of visitation and project outcomes, and use of gate keys. When landowners denied our request for access, we excluded the plot from further consideration.

When crews initiated plot visits, additional ownership issues often arose. In study areas with considerable private land, like Pennsylvania/New Jersey and South Carolina, as well as in Colorado where public lands, Bureau of Land Management lands in particular, were surrounded by private holdings, crews often came upon locked gates or “no trespassing” signs. In these scenarios, crews attempted to speak to local landowners to gain access while on the ground, but ultimately they forewent plot visitation if these access issues persisted.

In total, the number of plots visited within different ownership types varied by study area (table 9). Timber/paper company lands dominated in Maine and South Carolina. Most plots in Colorado and Oregon were on national forest lands, though national forests were visited in four of the six study areas. National forests visited included Francis Marion National Forest in South Carolina; White River and Routt National Forests in Colorado; Superior National Forest in Minnesota; and Deschutes, Fremont-Winema, Willamette, Rogue River-Siskiyou, and Umpqua, and National Forests in Oregon. Sample plots were most prevalent in state forest lands in the Minnesota and Pennsylvania/New Jersey study areas.

Table 9—Number of plots selected within each land ownership type within each study area

Landowner type	Study area					
	Colorado	Maine	Minnesota	Oregon	Pennsylvania/ New Jersey	South Carolina
Federal:						
National forest	38		13	50		15
National park					1	
Bureau of Land Management	8					
Military						1
State		4	30		31	6
County			7		3	
Local		1			4	
Private:						
Timber/paper		44				22
Other					11	6
Total plots visited	46	49	50	50	50	50

Plot Establishment

Once crews reached the closest or safest possible point from which to access a sample plot, they recorded a “landing zone” (LZ) global positioning system (GPS) coordinate using a handheld Garmin™ GPS unit. Crews then set a 10-ft proximity alarm using predetermined candidate plot “plot center” (PC) coordinates. From the LZ, crews travelled on foot toward the PC and stopped upon hearing the GPS proximity alarm. This “stopping point” (SP) was marked using GPS averaging and recorded into the field data collection application “CarboLoad” (see “Data Entry Using CarboLoad Application” section). CarboLoad automatically generated an azimuth and distance to the PC, and crews used a logger’s tape and compass to complete navigation to each PC. This process prevented undue crew bias while establishing each PC. To clearly locate the PC while on the plot and to facilitate any possible remeasurement, a small (0.25-inch diameter, 12-inch long) dark-colored fiberglass plot pin was inserted at the PC. From the PC, a 53-ft radius circular “large tree plot” and a 15-ft radius circular “small tree plot” were temporarily delineated using flagging at plot edges (fig. 15).

Field Data Collection

Once at each PC, crews collected data on living and dead standing trees, coarse woody debris, and live and dead vegetation cover; took plot photos; and recorded survey-grade GPS coordinates at each plot. Examples of plot photos from each of the sites are in appendix 4. Protocol specifics and additional details are available in the carbon monitoring system (CMS) field guide.³

Live and Dead Standing Trees

Live and dead tally trees consisted of tree species tallied by FIA within the continental United States. Within the large plot, all live and dead trees with a minimum height of 4.5 ft and a diameter at breast height (DBH = 4.5 ft) ≥ 5.0 inches were tallied. Within the small plot, all live and dead trees with a minimum height of 4.5 ft and a DBH ≥ 1.0 inch were tallied. In Colorado, woodland tree species were measured for diameter at root collar (DRC). Within the large plot, trees needed to have at least one stem ≥ 1.0 inch and a cumulative DRC > 5.0 inches. On the small plot, we measured trees with at least one stem ≥ 1.0 inch and a cumulative DRC ≥ 1.0 inch. Crew members measured and recorded the horizontal distance (HD) from the PC

³ Legner, K.; Andersen, H-E. 2015. Carbon monitoring system (CMS) field guide 2015. 82 p. On file with: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, University of Washington, Anderson Hall, Seattle, WA 98195.

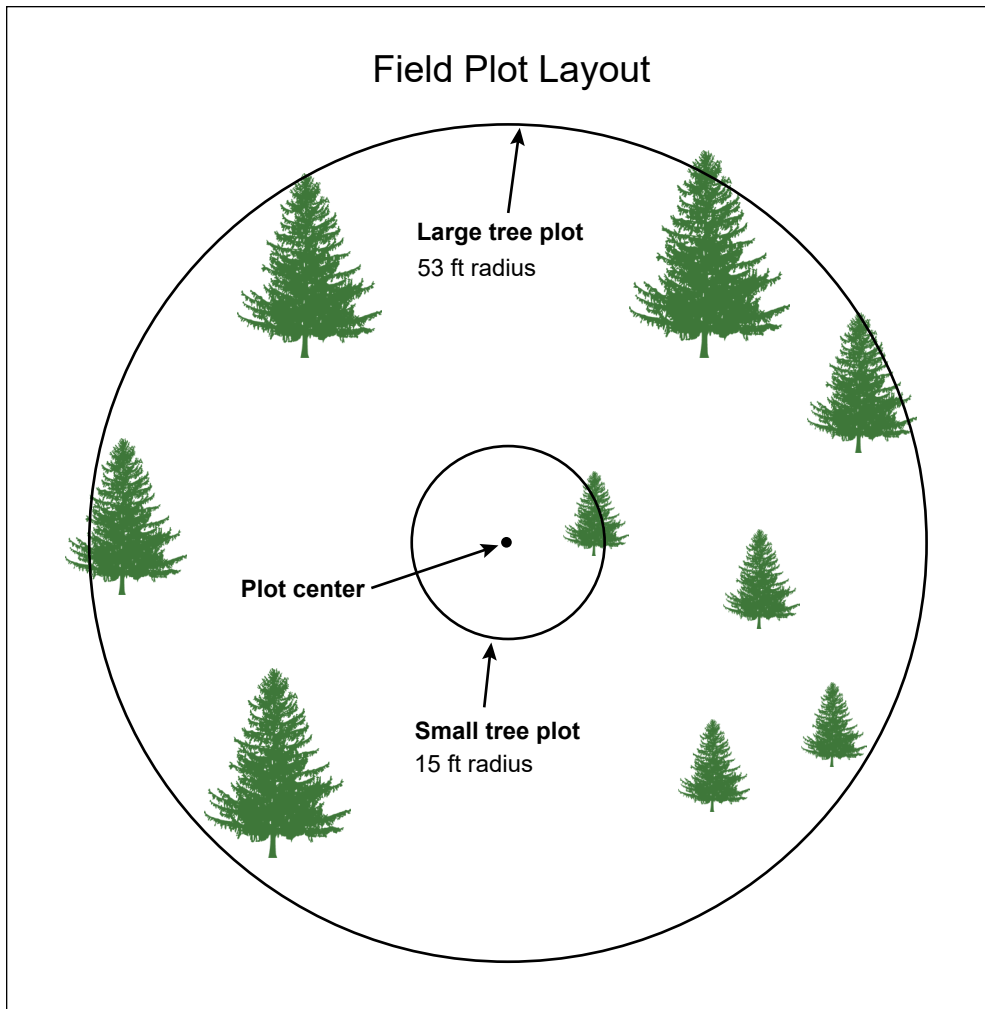


Figure 15—Layout of field plots.

pin to the midline of each tree bole (or geographic center of multistemmed woodland trees) and azimuth from the PC to the center of each tree base. A mark indicating breast height was made on each tree, and DBH was recorded to the nearest 0.1 inch. Tree length was measured with a TruPulse® 360° B laser and recorded to the nearest foot. If a tree was broken, the actual length of the standing tree was recorded as well as an estimate of the total length, had the tree remained intact. Using FIA definitions, decay class (1 through 5) was recorded for dead trees based upon the tree's current stage of decay. Percentage cull was recorded for all trees, missing and rotten cull for live trees, and only missing cull for dead trees. Additional parameters such as tree number, tree status, tree species, method used to determine length, and tree notes were recorded. Tree species codes were based on the USDA PLANTS database (USDA NRCS 2019). All trees encountered by crew members can be referenced by FIA code, USDA PLANTS code, or common and scientific name in appendix 5.

Coarse Woody Material

Coarse woody material was tallied along two transects radiating 90 and 360° from the PC. Decay class (1 through 5) was determined for each piece based on FIA definitions. The species for each piece was also recorded when identification was possible. Unknown dead conifer and unknown dead hardwood (broadleaf) codes were entered when identification was not possible. Crew members walked from the PC along each transect line toward the plot boundary and marked and measured the diameter of any woody material over 3 inches in diameter at the point of intersection with the transect that was also greater than 0.5 ft long. Outer diameter and any hollow diameters were recorded to the nearest 0.1 inch. One of two length classes was selected: 0.5 to 3 ft long or greater than 3 ft long. Crews also measured the slope distance from the PC to the central longitudinal axis of each piece.

Vegetation Profile

Crews completed a vegetation profile for each plot to describe the vegetation structure for all vascular plants within the large tree plot area. Crews used ocular methods to estimate canopy cover by growth habit and cover layer, closely following FIA field protocols for creating a vegetation profile. Growth habits consisted of live tally trees, dead tally trees, live nontally trees, dead nontally trees, live shrubs, dead shrubs, other growth habit (OGH), and all growth habits (AGH). OGH consisted of any forbs, nonwoody vines, ferns, graminoids, and subshrubs. AGH includes all aforementioned growth habits and represented a cumulative “bird’s eye” perspective of all live and dead growth forms present on the plot. Canopy cover of each growth habit was estimated separately within five distinct vertical cover layers: cover layer one (0 to 2.0 ft), cover layer two (2.1 to 6.0 ft), cover layer three (6.1 to 16.0 ft), cover layer four (16.1 ft and above), and aerial cover (total canopy coverage of particular growth habit) (fig. 16). Within each growth habit we recorded the dominant species and the maximum height of the tallest member of that growth habit to the nearest 0.1 ft.

Survey-Grade GPS and Photographs

Once all field measurements were collected, a Javad® Triumph-2 survey-grade GPS receiver was set up at plot center. The unit ran undisturbed for 20 minutes to collect a coordinate for plot center with less than 1 m error (Andersen et al. 2009). Final plot data included a photo from plot center in each cardinal direction as well as a 40 second 360° plot video with narration from plot center. A plot card with general access and composition information was filled out and photographed for digital storage.

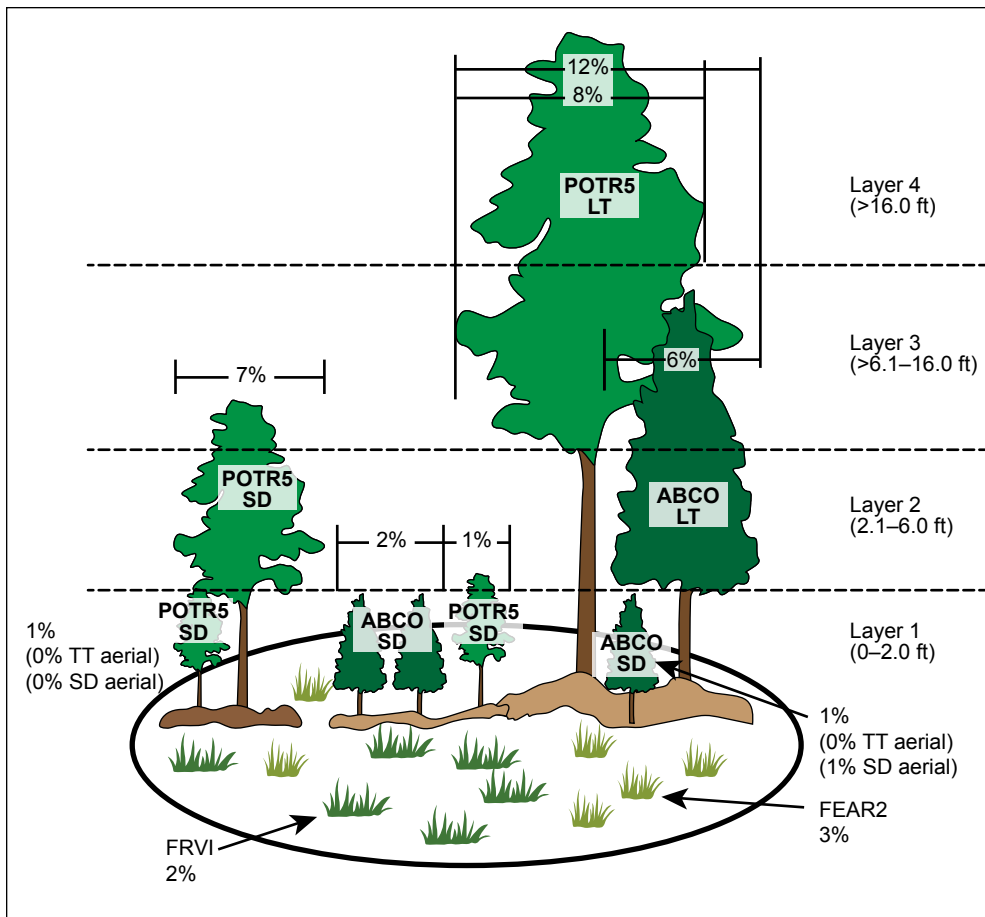


Figure 16—Depiction of plot divided into cover layers by vegetation height.

Data Entry Using CarboLoad Application

Instead of using paper forms, a data entry application nicknamed “CarboLoad” was developed for easy field data collection. CarboLoad was created using FileMaker Pro™ database software (version 13). Each plot had a standalone digital file created to collect data on plot establishment, navigation, and survey grade GPS coordinates, tree measurements, vegetation profile, and coarse woody material measurements.

Plot establishment—

Upon arrival at the SP, crews opened a blank CarboLoad file for the plot to be established. Once the plot number was selected from the CarboLoad home screen, the initial “Plot” tab opened (fig. 17). This tab was prefilled with the plot number, study area, and target latitude and longitude for the PC. A pick list under “Plot Status” was provided to select “sampled” to access the additional data collection tabs. Blanks were provided to fill in basic data collection information on sampling date and time, crew member names, completion status of each data collection item, and notes and photo attachments. Once all plot level data were completed and validated, CarboLoad checks provided assurance that the data entry was complete (fig. 18).

Plot

CarboLOAD version 4.3

	Validated	Complete	Sp. ID Pending
Plot	☐	☐	
Study Area	☐	☐	
Target Latitude	☐	☐	
Target Longitude	☐	☐	
Plot Status	☐	☐	
Plot Nonsampled Reason		☐	
Start Date		☐	
End Date		☐	
Crew Leader		☐	
Crew Member 1		☐	
Crew member 2		☐	
Crew member 3		☐	
Crew member 4		☐	
Crew member 5		☐	

Plot Notes 

Plot Attachments 

Figure 17—CarboLoad Plot tab upon arrival at plot. This tab provided spaces to enter basic plot level information.

Plot

CarboLOAD version 4.3

	Validated	Complete	Sp. ID Pending
Plot	☒	☒	
Study Area	☒	☒	
Target Latitude	☒	☒	
Target Longitude	☒	☒	
Plot Status	☒	☒	
Plot Nonsampled Reason		☒	
Start Date	☒	☒	
End Date	☒	☒	
Crew Leader	☒	☒	
Crew Member 1	☒	☒	
Crew member 2	☒	☒	
Crew member 3	☒	☒	
Crew member 4	☒	☒	
Crew member 5	☒	☒	

Plot Notes 

Plot Attachments 

Figure 18—CarboLoad Plot tab upon completion of plot.

GPS coordinates—

On the “Nav GPS” tab, navigation GPS coordinates from the handheld Garmin unit were entered into CarboLoad to assist in final navigation to the PC (fig. 19).

The “Survey GPS” tab was used to record position and timing of the survey-grade GPS (fig. 20).

Plot	Nav GPS	Survey GPS	Tree	Veg Profile	CWD 90	CWD 360
Nav GPS - Plot 4260						
Location Type	GPS ID	GPS Latitude	GPS Longitude	GPS Error	Offset Azimuth	Offset Distance
✓ LZ	008618	39.67384	-107.69968	0		
	Distance to Target	Azimuth to Target	GPS Notes			
	5496.8	45				
Location Type	GPS ID	GPS Latitude	GPS Longitude	GPS Error	Offset Azimuth	Offset Distance
✓ SP	008618	39.68249	-107.68365	0		
	Distance to Target	Azimuth to Target	GPS Notes			
	7.9	263				
Location Type	GPS ID	GPS Latitude	GPS Longitude	GPS Error	Offset Azimuth	Offset Distance
✓ PC	008618	39.68244	-107.68362	0		
	Distance to Target	Azimuth to Target	GPS Notes			
	24.8	309				

Figure 19—CarboLoad Navigation global positioning system (GPS) tab with data on landing zone (LZ), stopping point (SP), and plot center (PC) locations and their positions relative to the PC.

Plot	Nav GPS	Survey GPS	Tree	Veg Profile	CWD 90	CWD 360
Survey GPS - Plot 4260						
GPS Unit ID	Antenna Height	Time Started	Time Stopped	Distance to PC	Azimuth to PC	Survey GPS Notes
✓ 00469	6.15	10:45	11:06	0.0		

Figure 20—CarboLoad Survey global positioning system (GPS) tab with data on position of GPS unit and timing of data recording.

Tree data—

The CarboLoad “Tree” tab allowed for creation of an individual record for each tree at the plot (fig. 21). Trees were automatically numbered, and blanks were provided to insert information on tree status, tree species, final species ID, azimuth and horizontal distance from the PC, diameter at breast height, confirmation of diameter check, actual and total length of tree, and decay class and cull if necessary. Buttons were also available to add additional tree notes and other attachments, such as photos.

Plot	Nav GPS	Survey GPS	Tree	Veg Profile	CWD 90	CWD 360		
Trees - Plot 6293								
	Tree	Tree Status	Tree Species	Final ID	Azimuth	Horiz. Dist.	Diameter	Diameter Check
	1	1	PIPO	Yes	9	4.1	5.0	Measured
		Actual Length	Total Length	Length Method	Decay Class	Cull	Tree Notes	Attachments
	30	30	Both		0			
	Tree	Tree Status	Tree Species	Final ID	Azimuth	Horiz. Dist.	Diameter	Diameter Check
	2	1	PICO	Yes	9	8.0	6.1	Measured
		Actual Length	Total Length	Length Method	Decay Class	Cull	Tree Notes	Attachments
	50	50	Both		0			
	Tree	Tree Status	Tree Species	Final ID	Azimuth	Horiz. Dist.	Diameter	Diameter Check
	3	1	PICO	Yes	17	31.0	14.1	Measured
		Actual Length	Total Length	Length Method	Decay Class	Cull	Tree Notes	Attachments
	56	56	Both		0			
	Tree	Tree Status	Tree Species	Final ID	Azimuth	Horiz. Dist.	Diameter	Diameter Check
	4	1	PICO	Yes	35	19.0	12.6	Measured
		Actual Length	Total Length	Length Method	Decay Class	Cull	Tree Notes	Attachments
	63	63	Both		0			
	Tree	Tree Status	Tree Species	Final ID	Azimuth	Horiz. Dist.	Diameter	Diameter Check
	5	1	PIPO	Yes	40	17.2	20.0	Measured

Figure 21—CarboLoad Tree tab provided records for individual trees at each plot.

A unique attribute of the CarboLoad application was its ability to store records of tree and vegetation species information unique to each study area (including both native and nonnative species). While working on a tree record, the magnifying glass icon adjacent to the “Tree Species” blank could be selected and CarboLoad would enter the “Tree Species Lookup” page (fig. 22). Within this page, crew members could search by species code, genus, species, or common name if they were uncertain as to species identification or the exact species code. This convenient feature also provided a frequency rank, which showed how common this species was in the FIA region where the study area was located. Once a species code was selected, it autofilled into the “Tree” tab.

Tree		Show All Tree Species Lookup					
PI							
Species Symbol	Freq. Rank	Symbol Type	Genus	Species	Species Symbol	Common Name	
PIAL	35	Species	Pinus	albicaulis	PIAL	whitebark pine	
PIAT	46	Species	Pinus	attenuata	PIAT	knobcone pine	
PIBR	96	Species	Picea	breweriana	PIBR	Brewer spruce	
PICO	3	Species	Pinus	contorta	PICO	lodgepole pine	
PICO3	95	Species	Pinus	coulteri	PICO3	Coulter pine	
PIEN	17	Species	Picea	engelmannii	PIEN	Engelmann spruce	
PIFL2	96	Species	Pinus	flexilis	PIFL2	limber pine	
PIGL	96	Species	Picea	glauca	PIGL	white spruce	
PIJE	40	Species	Pinus	jeffreyi	PIJE	Jeffrey pine	
PILA	19	Species	Pinus	lambertiana	PILA	sugar pine	
PIMO3	18	Species	Pinus	monticola	PIMO3	western white pine	
PIMU	96	Species	Pinus	muricata	PIMU	Bishop pine	

Figure 22—CarboLoad Tree Species Look-up page accessed searchable database of tree species at each study area.

Vegetation data—

The vegetation profile was added into the “Veg Profile” tab within CarboLoad (fig. 23). The profile was divided into records by growth habit. Percentage cover by cover layer, dominant species by growth habit, maximum height of growth habit, and final species identification confirmation were entered by crews. As in the “Tree” tab, use of the magnifying glass icon adjacent to “Dominant Species” displayed the “Veg Profile Growth Habit” lookup page, where crews could search by species code, scientific name, or common name. Additionally, on this lookup page, species were divided

Plot	Nav GPS	Survey GPS	Tree	Veg Profile	CWD 90	CWD 360			
Veg Profile - Plot 6293									
	Growth Habit	Has Veg	Aerial Cover	Tally Max Length	Max Height	Cover Layer 1	Cover Layer 2	Cover Layer 3	Cover Layer 4
	LTT	Yes	37	104.0	104.0	4	16	32	35
	Dominant Species		Final Veg ID	Veg Notes	Attachments				
	PIPO		Yes						
	Growth Habit	Has Veg	Aerial Cover	Tally Max Length	Max Height	Cover Layer 1	Cover Layer 2	Cover Layer 3	Cover Layer 4
	DTT	Yes	18		8.9	14	9	1	0
	Dominant Species		Final Veg ID	Veg Notes	Attachments				
	PICO		Yes						
	Growth Habit	Has Veg	Aerial Cover	Tally Max Length	Max Height	Cover Layer 1	Cover Layer 2	Cover Layer 3	Cover Layer 4
	LNT	No							
	Dominant Species		Final Veg ID	Veg Notes	Attachments				
	Growth Habit	Has Veg	Aerial Cover	Tally Max Length	Max Height	Cover Layer 1	Cover Layer 2	Cover Layer 3	Cover Layer 4
	DNT	No							
	Dominant Species		Final Veg ID	Veg Notes	Attachments				
	Growth Habit	Has Veg	Aerial Cover	Tally Max Length	Max Height	Cover Layer 1	Cover Layer 2	Cover Layer 3	Cover Layer 4
	LSH	Yes	13		7.9	11	2	0	0

Figure 23—CarboLoad Veg Profile tab consists of records divided by growth habits (screen capture does not show all growth habits).

by growth habit to make it clear which species belonged to which growth habits. To assist with maximum height determinations, CarboLoad auto-filled the “Tally Max Length” box with the tallest live or dead tally tree measured in the “Tree” tab, and crews could select the auto-filled height as the “Max Height” once they verified it. The option to add vegetation notes and attachments was provided here as well.

Coarse woody material—

Data entry for coarse woody debris (CWD) transects was divided into two separate tabs within CarboLoad: “CWD 90” and “CWD 360” (fig. 24). Data entered in the “CWD 90” tab contained CWD measurements for the 53-ft transect that ran directly east (90°) from plot center, and “CWD 360” for the northbound transect. Within each CWD tab, CarboLoad auto-filled the CWD ID for each piece encountered sequentially. Crews filled in blanks for slope distance, decay class, CWD species, CWD diameter, hollow diameter, and length class. A button for CWD notes for each piece was available if additional information was recorded. As in the “Tree” and “Veg Profile” tabs, the magnifying glass icon next to “CWD Species” could be selected to bring up the “CWD Species” look-up page. Lastly, clicking on the “Residue Pile” icon opened the “Residue Pile” tab into which residue pile size, decay class, and dominant species information could be entered if piles were encountered.

Plot	Nav GPS	Survey GPS	Tree	Veg Profile	CWD 90	CWD 360	
CWD Transect 360, Plot 4260 Residue Pile							
CWD ID	Slope Distance	Decay Class	CWD Species	CWD Diameter	Hollow Diameter	Length Class	CWD Notes
1	19.1	3	PIED	6	0	1	
2	25.7	2	PIED	4	0	1	
3	27.8	2	PIED	3	0	1	
4	29.7	2	PIED	3	0	1	
5	30.3	2	PIED	6	0	1	

Figure 24—CarboLoad coarse woody debris (CWD) tab provides data entry for CWD encountered along each CWD transect (360° transect shown here).

CarboLoad Data Backup

Once data entry into CarboLoad was complete, crews saved backups of the data within the CarboLoad application and then synced data to the project server. This ensured that all data was backed up each day. Upon plot finalization, i.e., when all species were completely identified and plot card photographs were uploaded, crews completed a final data sync, and then a backup and final file of each plot were uploaded to the project Google Drive™ account. Synced data was directly imported into a Microsoft Access™ database and backup/final plot files could be accessed remotely by other project members for quality control and quality assurance.

Tree Height and Cover Estimations From Lidar Data

We postprocessed Javad Triumph-2 plot center coordinates using Javad Justin software for all sample plots. For each study area we obtained base station files from the closest GLONASS-enabled CORS base stations to complete differential correction of all coordinates.

The postprocessed plot center coordinates were used to extract fixed 53-ft-radius subsets of lidar data using Fusion lidar processing software (McGaughey 2015). Plot metrics were computed for each sample plot. Metrics included return counts, return elevations, and return intensity values. As in pre-field lidar processing, we used the metrics 90th percentile height (Elev.P90) to estimate stand heights and the percentage of first returns above 1.37 m (PC_{1st}) as a proxy for canopy cover at each plot. These values, averaged across plots by strata and study area (with associated standard errors (SE)), are shown in table 10. Oregon sample plots consistently showed the highest average P90 height across all strata (table 11). The remaining study area tree heights were more consistent with each other, although Maine and Minnesota tended toward the shortest trees. Although average PC_{1st} cover between study areas was more variable than height, Pennsylvania/New Jersey tended toward the highest cover while Colorado averaged lowest overall, especially within the highest cover class strata (31 to 35) (table 12).

Table 10—Mean plot level tree 90th percentile height at each study area by stratum

Stratum	90 th percentile height					
	Colorado	Maine	Minnesota	Oregon	Pennsylvania/ New Jersey	South Carolina
	----- Meters -----					
11	3.52 ± 0.42	5.90 ± 0.91	4.22 ± 0.38	8.35 ± 1.00	5.39 ± 1.20	3.34 ± 0.67
12	9.30 ± 1.23	7.02 ± 0.75	8.61 ± 0.35	12.95 ± 2.06	8.69 ± 0.75	9.23 ± 1.04
13	11.69 ± 0.35	12.01 ± 0.66	10.05 ± 1.17	20.83 ± 2.49	16.62 ± 1.22	14.83 ± 0.66
14	18.71 ± 0.38	14.07 ± 0.60	13.35 ± 1.47	26.57 ± 5.57	20.17 ± 0.41	18.10 ± 0.73
15	21.28 ± 1.32	19.23 ± 1.05	20.56 ± 1.06	37.40 ± 3.44	26.91 ± 1.37	24.42 ± 0.29
21	6.23 ± 0.15	4.65 ± 0.36	4.89 ± 0.65	8.07 ± 1.39	6.30 ± 1.24	4.83 ± 0.40
22	10.26 ± 1.11	7.40 ± 0.40	8.32 ± 0.68	16.62 ± 2.81	8.18 ± 0.32	8.84 ± 2.09
23	15.57 ± 0.49	11.53 ± 0.32	12.19 ± 0.25	23.96 ± 3.08	14.72 ± 0.42	15.15 ± 0.56
24	18.51 ± 0.40	13.26 ± 0.56	16.84 ± 1.44	31.34 ± 0.73	18.92 ± 0.47	19.45 ± 1.52
25	22.68 ± 0.63	17.41 ± 0.37	23.27 ± 1.29	41.27 ± 1.94	30.04 ± 1.78	26.51 ± 1.49
31	7.15 ± 0.32	5.75 ± 0.37	6.49 ± 0.81	10.18 ± 0.36	5.73 ± 0.93	6.64 ± 0.34
32	10.67 ± 0.49	10.53 ± 0.36	8.95 ± 0.62	22.82 ± 1.66	13.18 ± 1.34	11.88 ± 0.72
33	14.61 ± 1.06	12.45 ± 1.13	13.12 ± 0.65	30.81 ± 2.06	19.56 ± 0.84	15.93 ± 1.06
34	19.11 ± 1.16	17.98 ± 0.40	17.44 ± 0.88	42.70 ± 3.56	25.73 ± 1.14	23.77 ± 0.32
35	24.13 ± 1.12	20.94 ± 0.91	20.23 ± 0.94	51.13 ± 3.25	33.26 ± 2.27	27.74 ± 1.45

Note: Extracted from lidar data using the metric Elev.P90.

Strata are numbered using cover class as the first digit and height class as the second digit. Increasing values indicate a higher percentage of cover and greater tree height

Field measurements were collected in U.S. units to maintain consistency with FIA procedures. Lidar percentiles are reported in metric units because this is how these data were delivered.

Table 11—Mean plot level percentage of canopy cover at each study area by stratum

Stratum	Percentage cover					
	Colorado	Maine	Minnesota	Oregon	Pennsylvania/ New Jersey	South Carolina
	----- <i>Percent ± SE</i> -----					
11	28.88 ± 4.67	31.91 ± 2.51	18.57 ± 3.18	29.90 ± 3.18	32.09 ± 2.61	17.55 ± 2.37
12	34.90 ± 7.65	18.53 ± 6.25	32.38 ± 6.99	40.47 ± 17.01	37.07 ± 3.16	23.54 ± 6.78
13	23.73 ± 6.55	29.02 ± 4.29	22.38 ± 1.91	40.44 ± 7.23	31.82 ± 5.48	33.61 ± 4.34
14	37.52 ± 2.65	28.87 ± 7.08	29.66 ± 7.12	46.37 ± 12.25	27.47 ± 7.70	24.03 ± 0.29
15	32.50 ± 5.13	24.62 ± 4.48	23.89 ± 7.87	25.63 ± 4.23	24.77 ± 4.76	18.96 ± 1.87
21	47.00 ± 3.76	56.94 ± 3.90	53.73 ± 4.26	54.03 ± 9.05	59.51 ± 6.73	57.65 ± 6.82
22	58.84 ± 4.75	56.37 ± 2.78	54.45 ± 0.94	41.62 ± 0.90	54.69 ± 5.64	61.18 ± 7.14
23	54.56 ± 3.04	57.91 ± 5.40	58.69 ± 5.39	50.86 ± 4.34	68.35 ± 3.04	53.47 ± 6.41
24	56.65 ± 9.46	54.32 ± 3.43	63.82 ± 0.63	52.25 ± 3.26	62.79 ± 2.30	66.42 ± 3.3
25	59.35 ± 4.27	59.87 ± 2.69	61.14 ± 5.88	54.29 ± 7.99	58.18 ± 9.65	54.52 ± 7.24
31	80.01 ± 3.31	87.47 ± 5.95	82.34 ± 5.06	79.12 ± 4.37	80.38 ± 4.61	85.60 ± 3.73
32	77.31 ± 0.64	93.26 ± 6.05	93.92 ± 1.49	80.87 ± 9.79	83.73 ± 5.60	95.94 ± 1.80
33	71.70 ± 1.29	88.70 ± 0.57	92.15 ± 3.78	86.37 ± 5.50	97.48 ± 1.59	91.31 ± 6.54
34	79.17 ± 2.54	92.70 ± 4.83	79.73 ± 8.70	76.09 ± 5.00	98.77 ± 0.59	97.93 ± 1.29
35	73.63 ± 3.47	94.63 ± 4.20	89.70 ± 2.49	94.95 ± 1.65	95.92 ± 2.52	97.71 ± 0.36

SE = standard error.

Table 12—Mean plot level tree biomass at each study area by stratum

Stratum	Tree biomass					
	Colorado	Maine	Minnesota	Oregon	Pennsylvania/ New Jersey	South Carolina
	----- <i>Megagrams per hectare ± SE</i> -----					
11	20.24 ± 2.55	7.99 ± 4.39	6.4 ± 0.90	21.04 ± 3.07	48.02 ± 14.08	2.10 ± 1.23
12	20.82 ± 7.02	13.60 ± 6.36	12.49 ± 4.21	43.05 ± 7.90	57.17 ± 3.46	8.71 ± 3.21
13	41.27 ± 19.46	29.12 ± 6.61	13.30 ± 3.83	141.30 ± 52.95	63.21 ± 29.65	43.58 ± 2.08
14	123.40 ± 14.36	32.68 ± 2.06	20.78 ± 8.74	184.56 ± 52.93	59.71 ± 35.47	58.10 ± 11.60
15	118.93 ± 8.45	56.51 ± 7.46	31.31 ± 9.09	119.20 ± 20.56	62.49 ± 15.94	48.16 ± 5.22
21	44.92 ± 6.89	17.29 ± 13.06	7.18 ± 2.93	108.01 ± 53.66	45.70 ± 4.66	13.67 ± 4.20
22	82.34 ± 31.18	35.73 ± 12.38	37.05 ± 13.15	71.68 ± 16.26	47.84 ± 3.66	37.96 ± 18.21
23	105.82 ± 33.40	47.71 ± 14.01	75.35 ± 1.64	150.37 ± 28.79	92.16 ± 9.84	40.27 ± 19.81
24	124.53 ± 26.71	48.78 ± 2.62	52.80 ± 9.54	362.45 ± 121.42	43.22 ± 35.89	111.69 ± 4.62
25	173.57 ± 44.94	73.08 ± 2.34	86.37 ± 21.50	301.03 ± 22.39	134.38 ± 31.34	163.14 ± 37.11
31	44.08 ± 22.14	65.98 ± 13.01	28.01 ± 6.62	91.16 ± 17.71	81.70 ± 8.21	31.36 ± 5.65
32	60.84 ± 24.74	139.32 ± 37.25	65.99 ± 13.62	256.16 ± 95.49	85.11 ± 17.24	82.25 ± 20.37
33	93.83 ± 20.62	119.36 ± 3.91	86.44 ± 4.25	285.49 ± 34.86	192.96 ± 28.00	86.29 ± 16.37
34	202.64 ± 32.08	157.55 ± 24.46	125.48 ± 37.53	459.85 ± 18.82	240.89 ± 12.97	231.68 ± 10.03
35	218.52 ± 34.48	178.80 ± 27.87	119.14 ± 29.91	649.60 ± 84.94	294.60 ± 41.41	285.69 ± 14.73

SE = standard error.

Note: Strata are numbered using cover class as the first digit and height class as the second digit. Increasing values indicate a higher percentage of cover and greater tree height.

Biomass Calculations

Standing Tree Biomass

There are a variety of methods for estimating tree biomass. Prior to 2009, most U.S. carbon inventories used the national-scale biomass regression equations of Jenkins et al. (2003, 2004). Currently, FIA estimates biomass with a biomass expansion factor approach called the component ratio method (CRM) (Heath et al. 2009, Woodall et al. 2011). This approach converts tree volume estimates to biomass via incorporation of bole wood and bark specific gravities (Miles and Smith 2009), tree tops and limbs biomass (Jenkins et al. 2003), and stump volume estimates (Raile 1982). We used the current FIA approach to estimate standing tree biomass.

Standing tree biomass on a plot basis averaged within each stratum by study area ($\pm$ one standard error) ranged from 2.10 ± 1.23 Mg/ha for strata 11 plots in South Carolina, up to 649.60 ± 84.94 Mg/ha for strata 35 plots in Oregon (table 13). Oregon strata averaged the highest biomass across all study areas, except for strata 11, 12, and 22. Within these low-cover/low-height strata, Pennsylvania/New Jersey or Colorado plots averaged highest. Maine and Minnesota strata typically had the lowest standing tree biomass, with some exceptions.

Table 13—Mean plot-level coarse woody debris (CWD) biomass and percentage of sample plots containing CWD at each study area

Study area	Plots with CWD	Biomass
	<i>Percent</i>	<i>Mean megagrams per hectare $\pm$ SE</i>
Colorado	83	37.82 ± 6.74
Maine	90	26.67 ± 4.29
Minnesota	76	21.86 ± 3.54
Oregon	92	31.27 ± 5.38
Pennsylvania/New Jersey	46	23.33 ± 6.48
South Carolina	56	16.29 ± 3.48

SE = standard error.

We also determined the percentage of standing tree biomass represented by tree species across all sample plots within each study area (figs. 25 through 30) (see app. 5 for the scientific names of tree species identified in this report). South Carolina plot biomass was dominated by pine species (fig. 25): loblolly pine (63 percent), and longleaf pine (8 percent), likely a result of the densely forested pine plantations that were prevalent throughout the study area. Thirteen oak species dominated the remaining biomass (14 percent), with laurel oak, cherrybark oak, and water oak representing 9 percent of that alone.

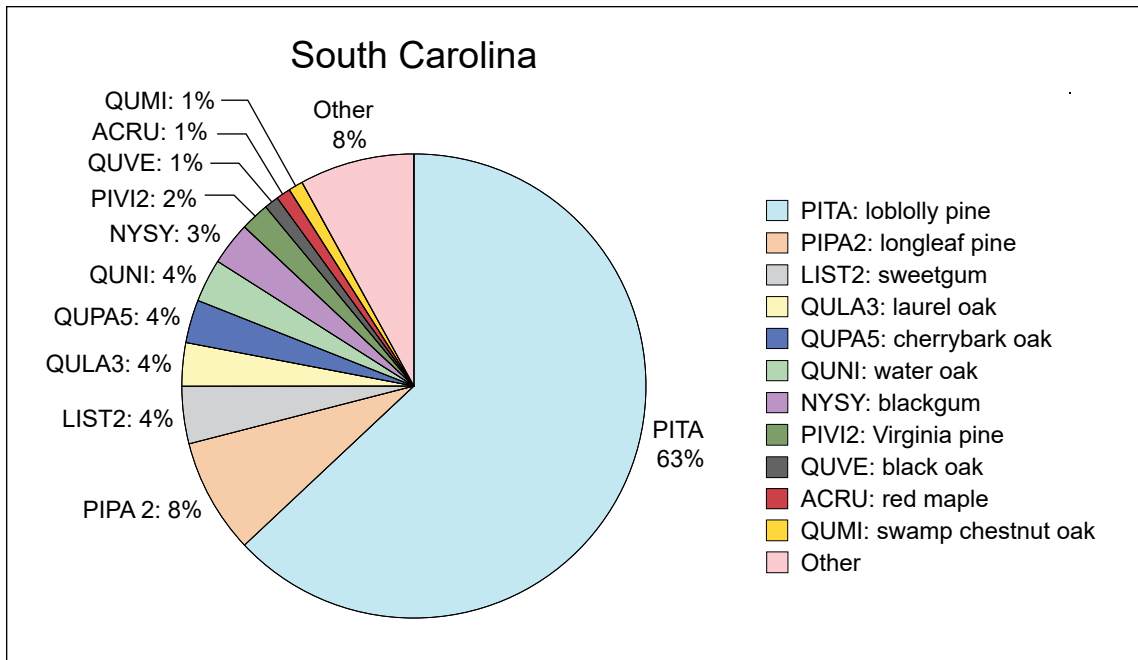


Figure 25—Percentage of total measured tree biomass by tree species in South Carolina. All species representing <1.0 percent total biomass are listed as “other.” USDA PLANTS database tree species codes were used.

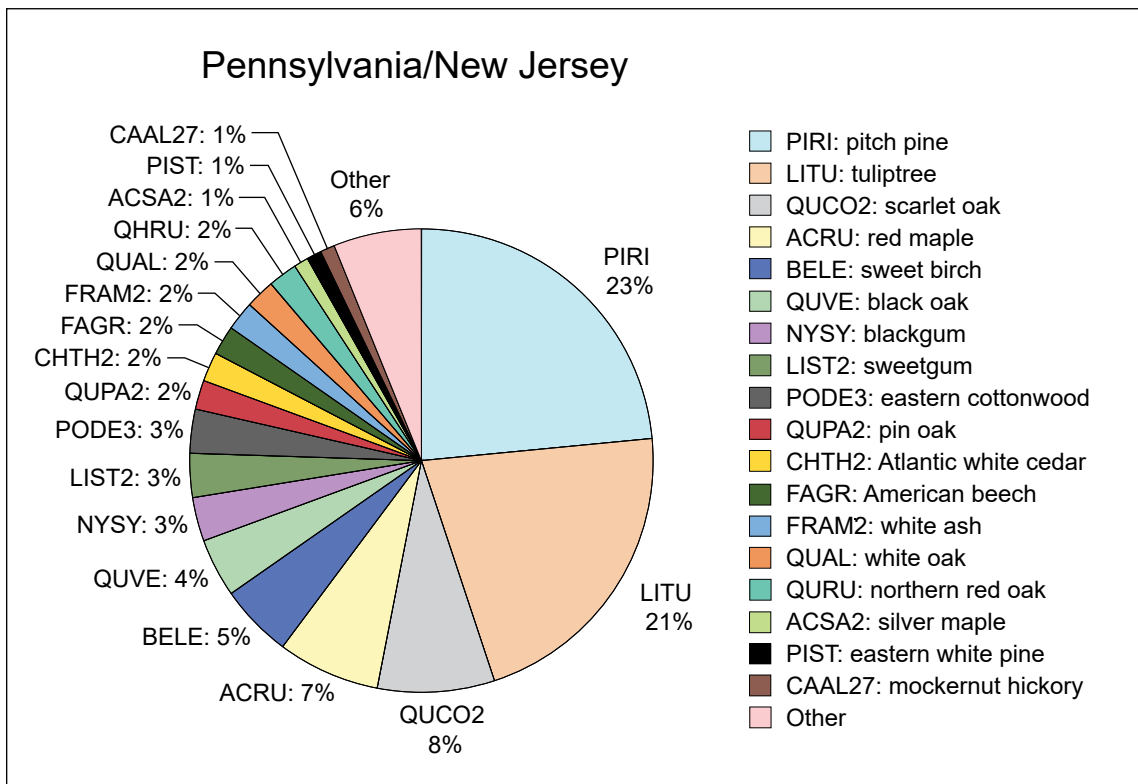


Figure 26—Percentage of total measured tree biomass by tree species in Pennsylvania/New Jersey. All species representing <1.0 percent total biomass are listed as “other.” USDA PLANTS database tree species codes were used.

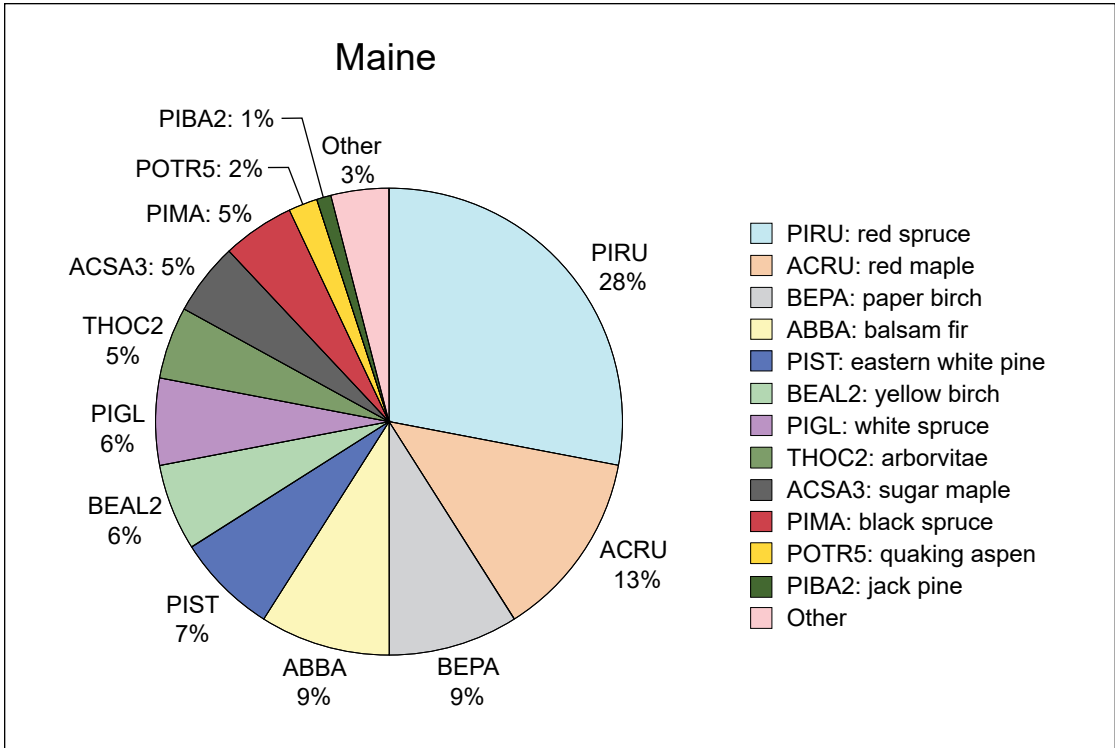


Figure 27—Percentage of total measured tree biomass by tree species in Maine. All species representing <1.0 percent total biomass are listed as “other.” USDA PLANTS database tree species codes were used.

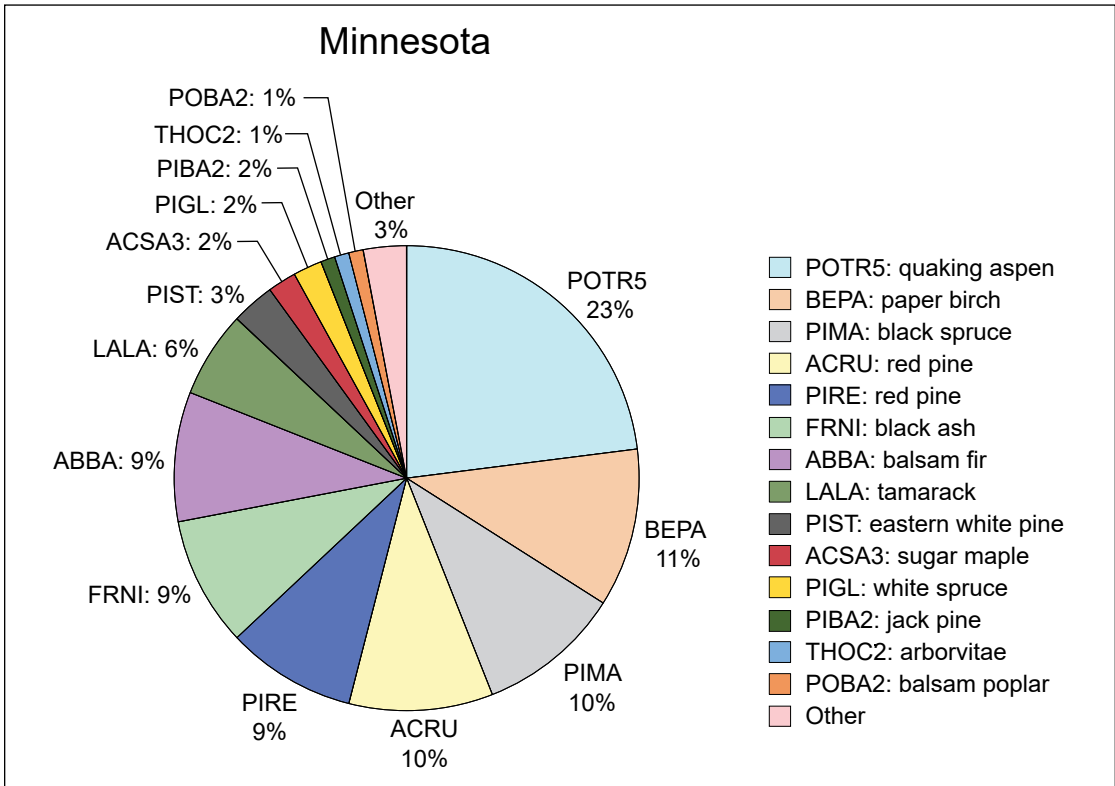


Figure 28—Percentage of total measured tree biomass by tree species in Minnesota. All species representing <1.0 percent total biomass are listed as “other.” USDA PLANTS database tree species codes were used.

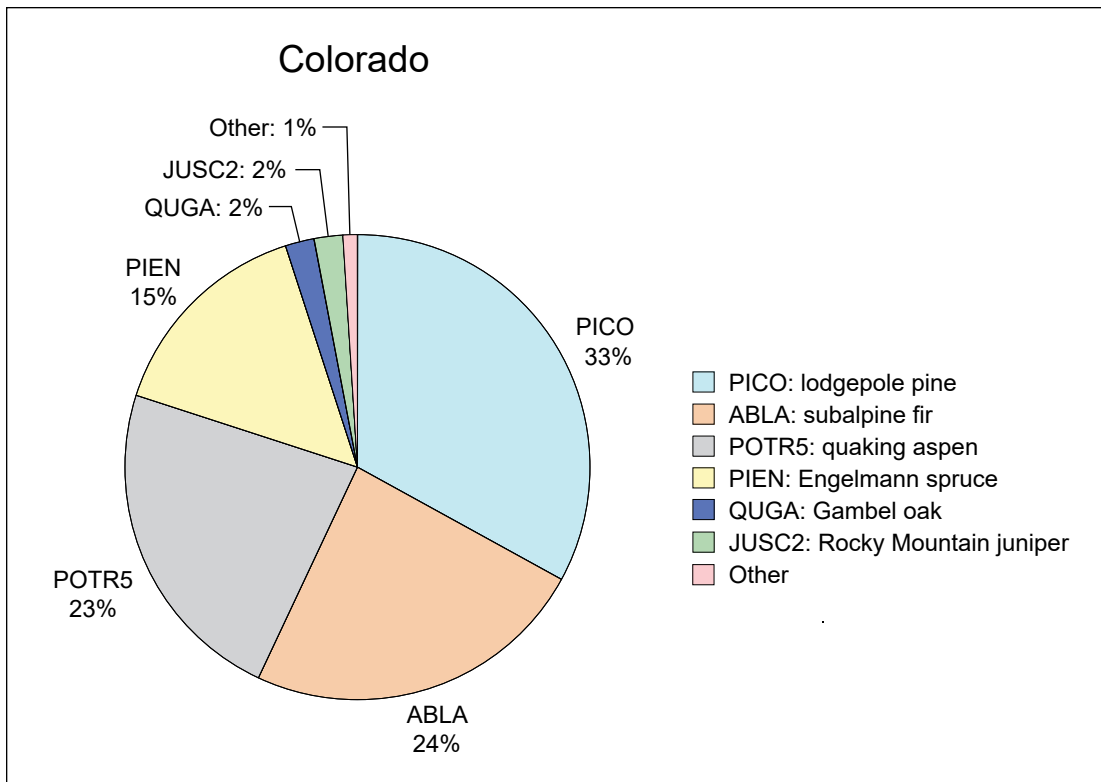


Figure 29—Percentage of total measured tree biomass by tree species in Colorado. All species representing <1.0 percent total biomass are listed as “other.” USDA PLANTS database tree species codes were used.

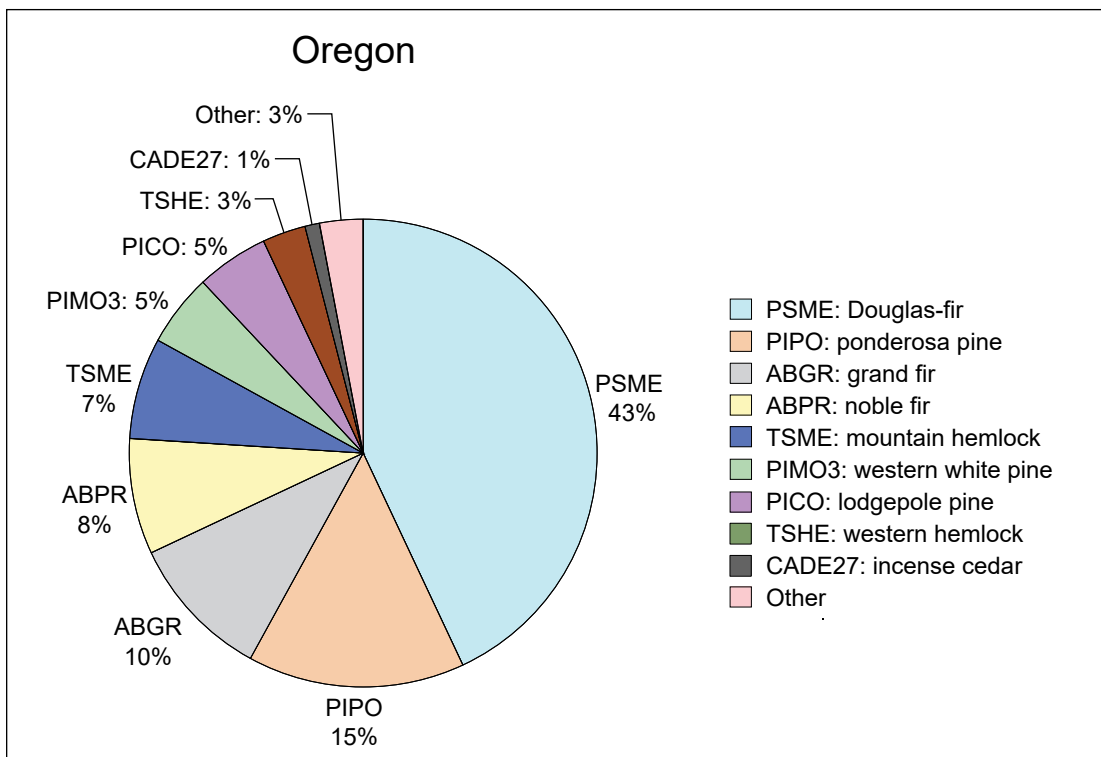


Figure 30—Percentage of total measured tree biomass by tree species in Oregon. All species representing <1.0 percent total biomass are listed as “other.” USDA PLANTS database tree species codes were used.

Pennsylvania/New Jersey had the largest number of species measured, at 40 unique species (fig. 26). Many plots were located in the Pine Barrens region of New Jersey, and the dominant species here was pitch pine (23 percent). Among hardwood forests, tuliptree (21 percent), scarlet oak (8 percent), red maple (7 percent), and sweet birch (5 percent) dominated.

The number of species measured decreased in the northern states of Maine and Minnesota. In Maine, coniferous trees represented 61 percent of total biomass, with red spruce (28 percent) dominating (fig. 27). Maple and birch species comprised the majority of deciduous trees: red maple (13 percent), paper birch (9 percent), and yellow birch (6 percent). Minnesota plots had similar species composition to that of Maine (fig. 28), however deciduous trees now represented 58 percent of total biomass with quaking aspen (23 percent) dominating, and paper birch (11 percent) and red maple (10 percent) again heavily present.

Colorado had only 12 total species measured (fig. 29), which was the fewest of any study area. Biomass was heavily dominated by conifers: lodgepole pine (33 percent), subalpine fir (24 percent), and Engelmann spruce (15 percent). The main deciduous tree was again quaking aspen (23 percent), found in the dense Colorado aspen groves.

Finally, Oregon was dominated exclusively by conifers (fig. 30), with Douglas-fir (43 percent) and grand fir (10 percent) found mainly in the western part of the study area and ponderosa pine (15 percent) in the east.

Coarse Woody Material Biomass

We estimated CWD biomass for each plot on a per-unit-area basis using the current FIA method (Woodall and Monleon 2008). The percentage of sample plots that contained CWD ranged widely from a low of 46 percent in Pennsylvania/New Jersey up to 92 percent in Oregon (table 14). Overall, the study areas with more heavily managed forests and developed areas (Minnesota, Pennsylvania/New Jersey, and South Carolina) had fewer sample plots containing CWD. In terms of CWD plot biomass, the lowest mean biomass was in South Carolina at 16.29 ± 3.48 Mg/ha, and the highest was in Colorado at 37.82 ± 6.74 Mg/ha. Again, Minnesota, Pennsylvania/New Jersey, and South Carolina had lower mean plot biomass than the study areas with more remote and undeveloped areas (Colorado, Maine, and Oregon).

Table 14—Variables and R² values of multiple regression models fitted as a square root of biomass and back transformed for each study area

Model	Var1	Var2	Multiple R ²	Back transformed model	Back transformed multiple R ²
			<i>Percent</i>		<i>Percent</i>
Biomass_CO ^{1/2}	Elev.mean	PC _{all}	77	Biomass_CO	77
Biomass_ME ^{1/2}	Elev.mean	PC _{1st}	86	Biomass_ME	88
Biomass_MN ^{1/2}	Elev.mean × PC _{all/1st}	—	81	Biomass_MN	82
Biomass_OR ^{1/2}	Elev.mean	PC _{all/1st}	84	Biomass_OR	84
Biomass_PANJ ^{1/2}	Elev.P30	PC _{all/1st}	72	Biomass_PANJ	81
Biomass_SC ^{1/2}	Elev.P50	Elev.P50 × PC _{all/1st}	92	Biomass_SC	91
Biomass_All ^{1/2}	Elev.P80	Elev.P80 × PC _{1st}	77	Biomass_All	78

Significance of each variable = 0.001.

Biomass Regressions

The trends between lidar height and cover metrics appear to corroborate standing tree biomass calculated from field data. Although we focus on biomass here, these results apply to carbon estimation if we assume tree carbon = 0.5 × tree biomass (Birdsey 1992). To determine the strength of various lidar metrics to predict biomass, we ran multiple regression analysis in R software (R Core Team 2015) using a best subsets regression. Models were fit as a square root of biomass, and subsequently back transformed. Each study area was evaluated independently, and then all study areas were evaluated together. In each study area, a lidar tree height metric and a cover metric significantly predicted standing tree biomass (table 14).

The majority of models (Colorado, Maine, Minnesota, and Oregon) used mean height (Elev.mean) although the 30th, 50th, and 80th percentile heights (Elev.P30, Elev.P50, and Elev.P80) were used in Pennsylvania/New Jersey, South Carolina, and for all study areas together, respectively. The cover metrics included percentage of first returns above 1.37 ft (PC_{1st}), percentage of all returns above 1.37 ft (PC_{All}), or all returns above 1.37 ft/total first returns × 100 (PC_{All/1st}). These variables moderately strongly to strongly predicted the square root of biomass, with R² (percentage) values ranging from 72 percent for Pennsylvania/New Jersey to 92 percent for South Carolina. For all study areas together, the prediction was also moderately strong at 77 percent. When back transformed, the R² (percentage) values were still high, from 77 percent for Colorado to 91 percent for South Carolina, with all study areas increasing slightly to 78 percent.

Discussion and Conclusions

This report describes a field data collection protocol designed to obtain plot-based measurements of forest tree biomass to support lidar-assisted estimation of forest biomass/carbon at the state or regional scale. Given the limited number of plots at each site (approximately 50 per site), we used both the NLCD land cover classification and the lidar strip sample to distribute these plots across the range of structural covariates (height and cover) observed at each site. This approach was intended to produce more robust, and less biased, lidar-based biomass/carbon models that could be applied across the entire site. It should be noted that because our primary objective was to distribute this relatively small number of field plots across the range of forest structural conditions within each site to support lidar modeling, we did not attempt to select the sample as a true probability sample of the total population of forest land, as is the case with FIA. For example, owing to budget and time constraints, only areas within a reasonable distance from roads were sampled. However, the stratified plot selection design ensured that a representative set of lidar-based structural conditions were included in the sample.

It is expected that these data will be used to support a variety of carbon monitoring activities, including assessment of forest change and calibration/validation of spaceborne lidar (e.g., Global Ecosystem Dynamics Instrument) (Patterson et al. 2019).

Acknowledgments

This report is a result of months of work by technicians and collaborators across the United States. Field technicians Brent Borden, Michael Hicks, Ryan Manual, and Rachel Mickey are responsible for our quality field data collection. Warren Cohen, Andrew Cooke, Bob McGaughey, Steve Reutebuch, Chad Babcock, L. Monika Moskal, Megan O'Shea, and Chad Oukrop provided invaluable pre- and post-field data processing or logistical assistance. Kevin Dobelbower created and maintained our field data entry program and database CarboLoad. Kurt Campbell determined our biomass estimates using FIA resources. Local training and knowledge in each study area was provided by Byron Rominger, Joseph Kernan, Michael Gallagher, Ken Clark, Jeff Harriman, Melissa Powers, Christopher Bergquist, and Aaron Wykhuis. Finally, a big thank you to all the local landowners and managers who assisted our field crews in accessing plots and staying safe throughout the United States.

U.S. Equivalents

When you have:	Multiply by:	To get:
Meters (m)	3.28	Feet
Hectares (ha)	2.47	Acre
Square kilometers (km ²)	.386	Square miles
Megagrams per hectare (Mg/ha)	.446	Tons per acre

Metric Equivalents

When you have:	Multiply by:	To get:
Inches (in)	2.54	Centimeters
Feet (ft)	.305	Meters

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Appendix 1: Strata Height and Cover Boundaries by Study Area With Sample Plots Colored

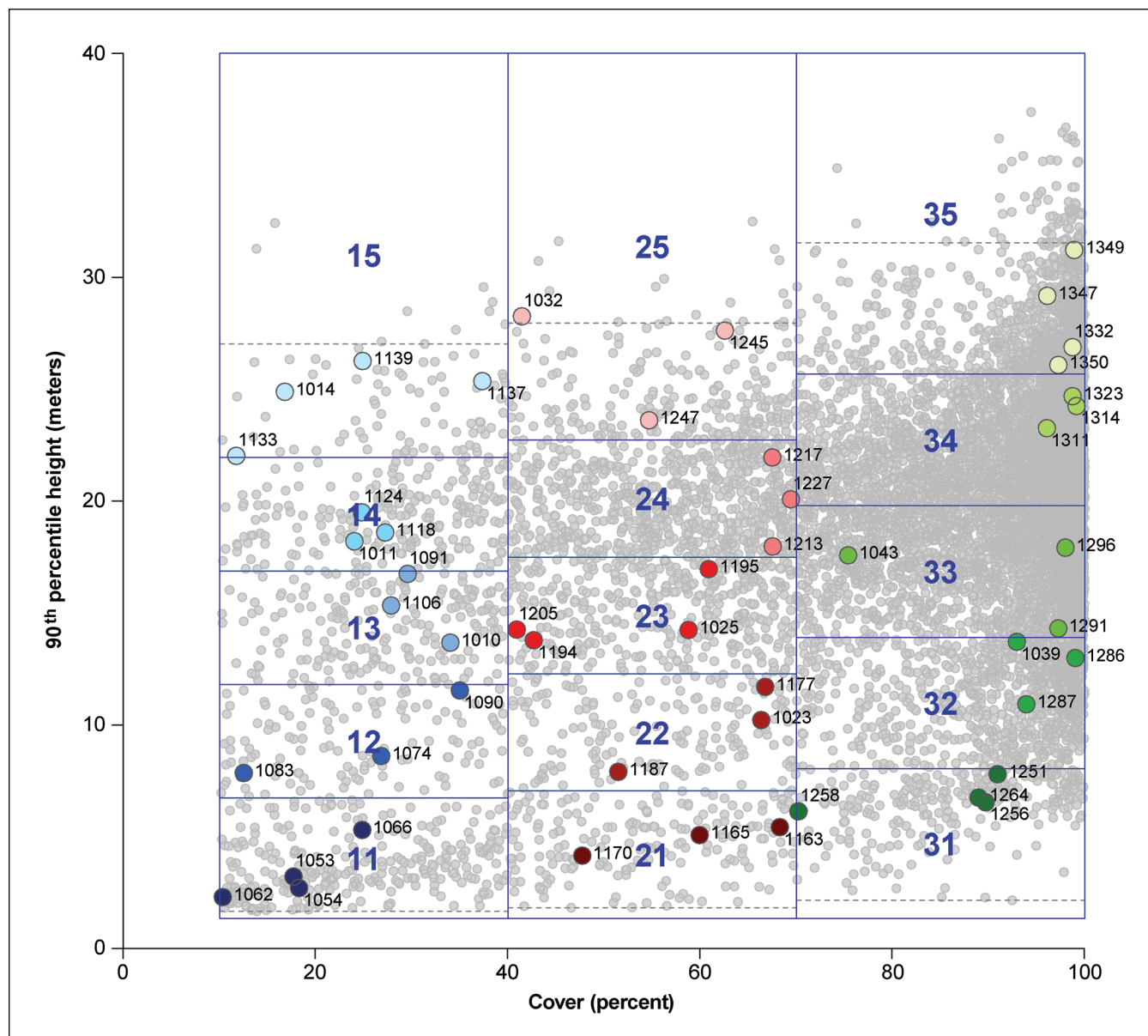


Figure 31—Distribution of sample lidar height (P90) and cover (PC_{1st}) metrics divided into strata for the South Carolina study area.

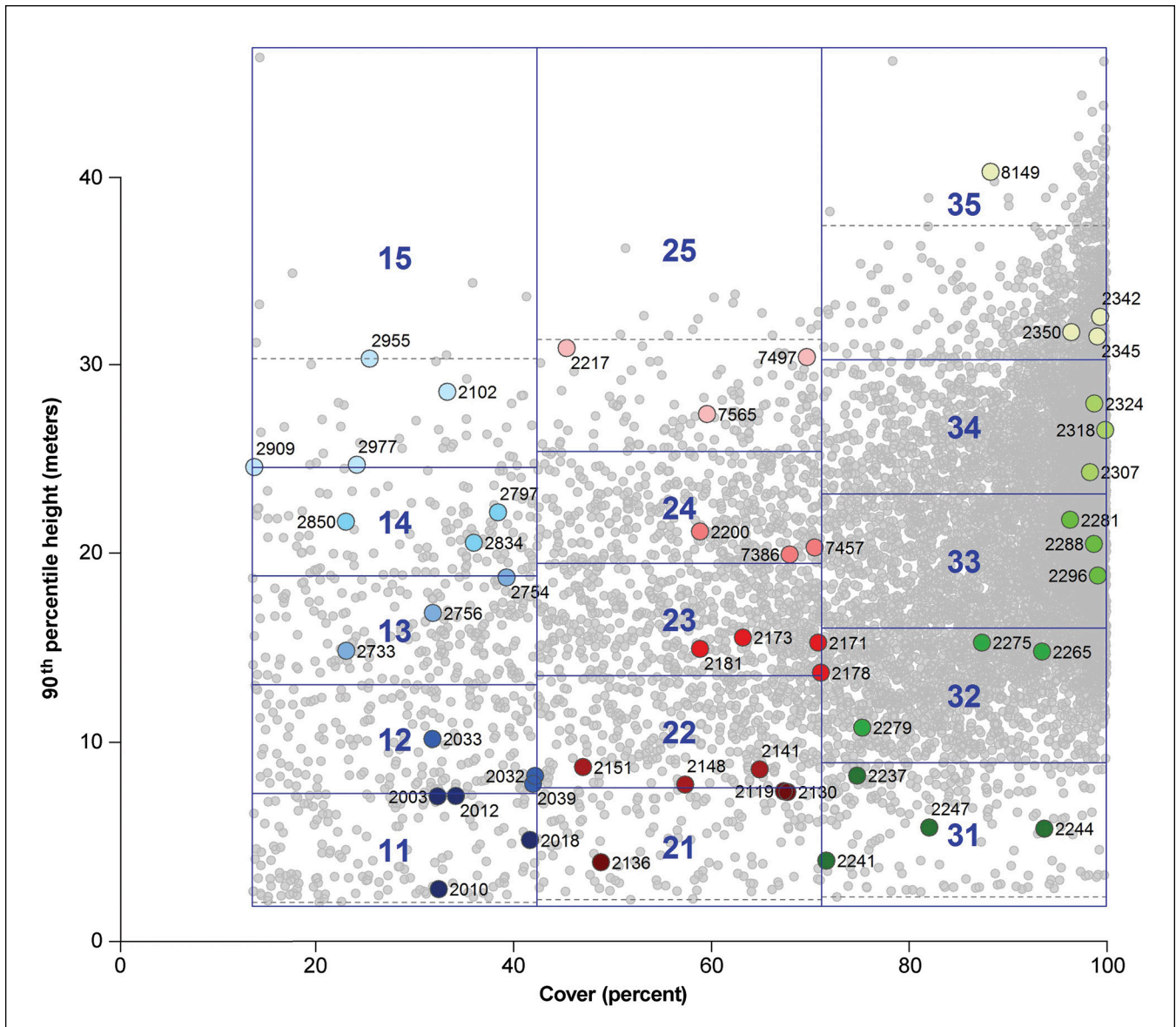


Figure 32—Distribution of sample lidar height (P90) and cover (PC_{1st}) metrics divided into strata for the Pennsylvania/New Jersey study area.

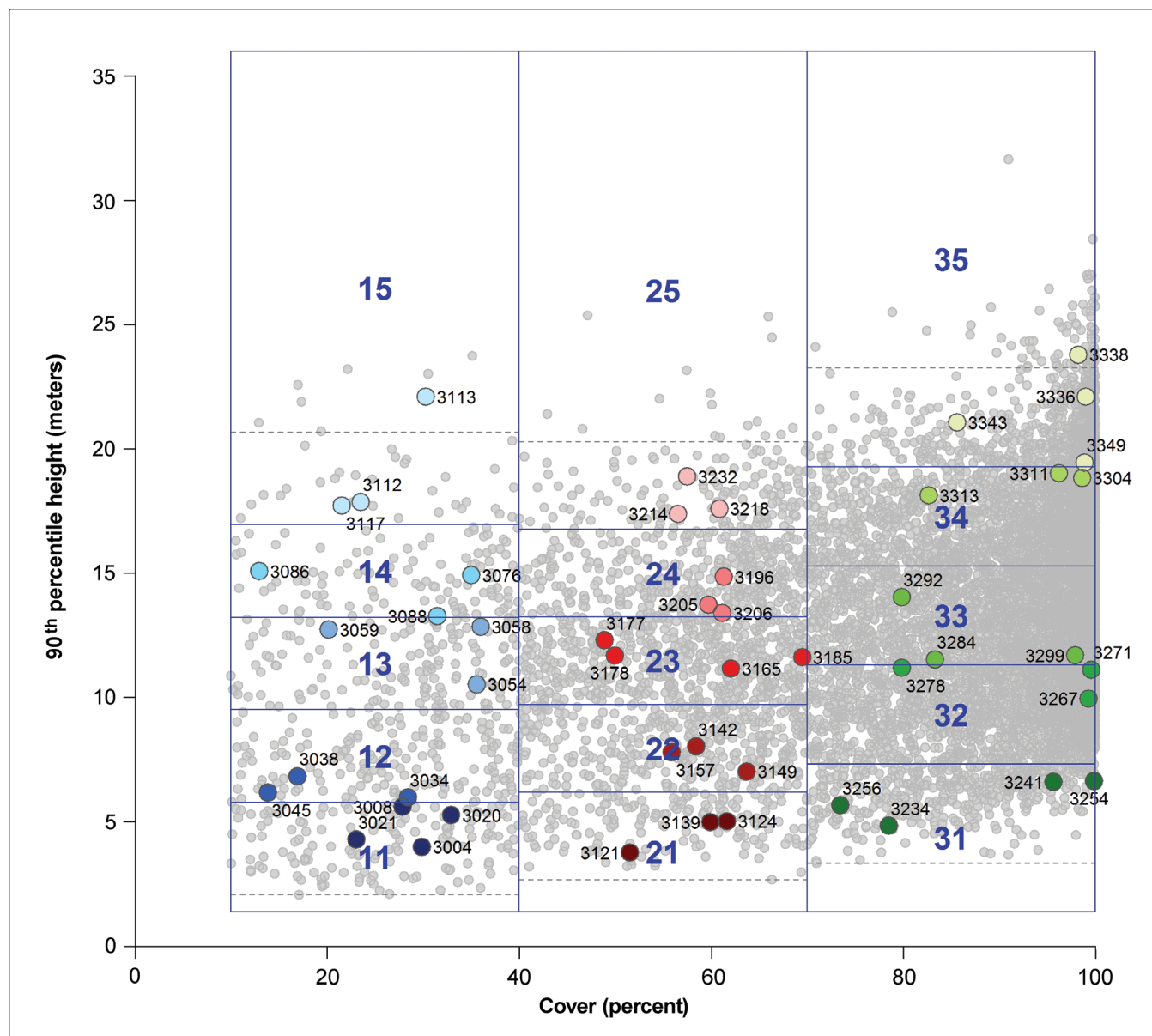


Figure 33—Distribution of sample lidar height (P90) and cover (PC_{1st}) metrics divided into strata for the Maine study area.

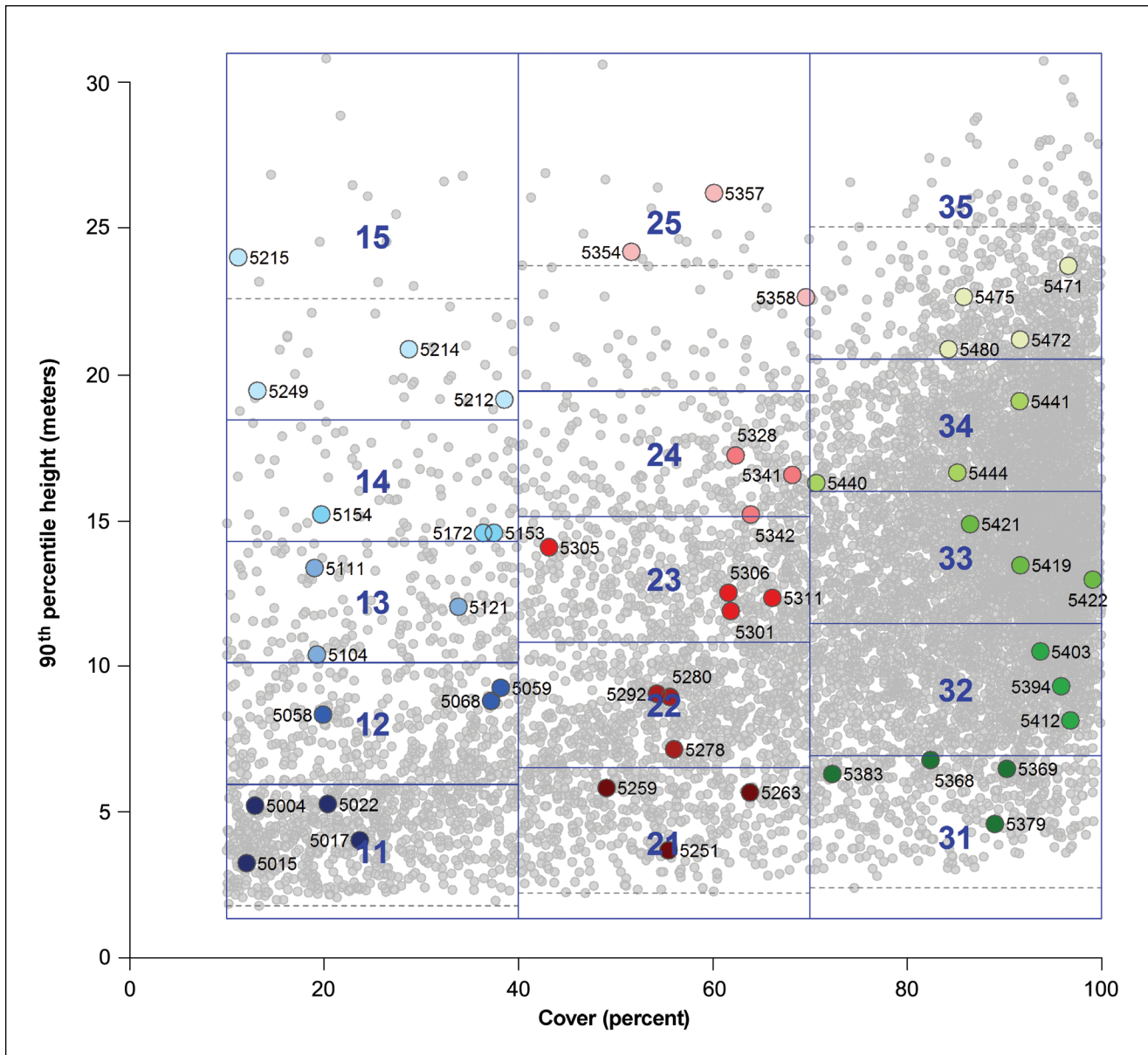


Figure 34—Distribution of sample lidar height (P90) and cover (PC_{1st}) metrics divided into strata for the Minnesota study area.

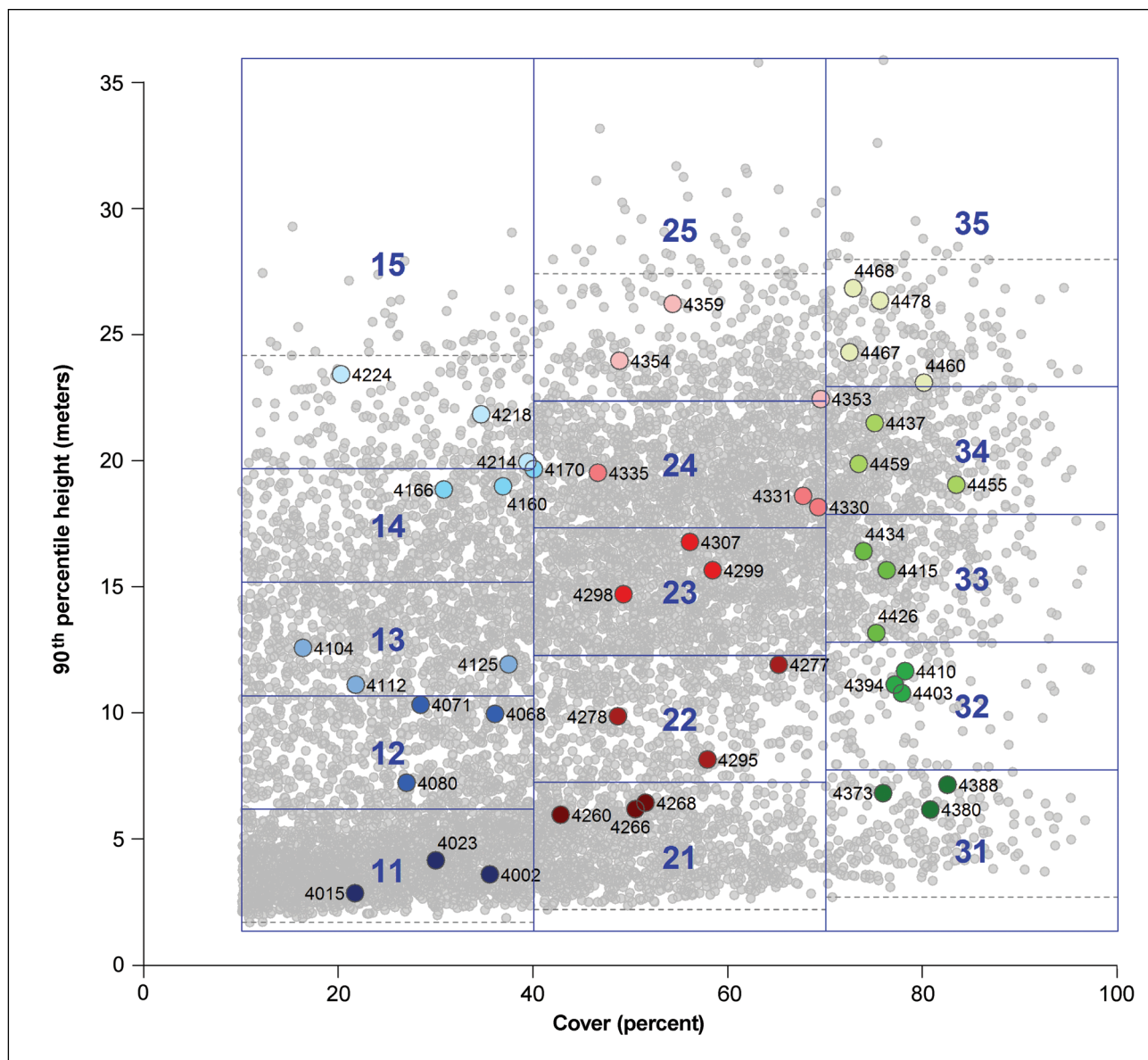


Figure 35—Distribution of sample lidar height (P90) and cover (PC_{1st}) metrics divided into strata for the Colorado study area.

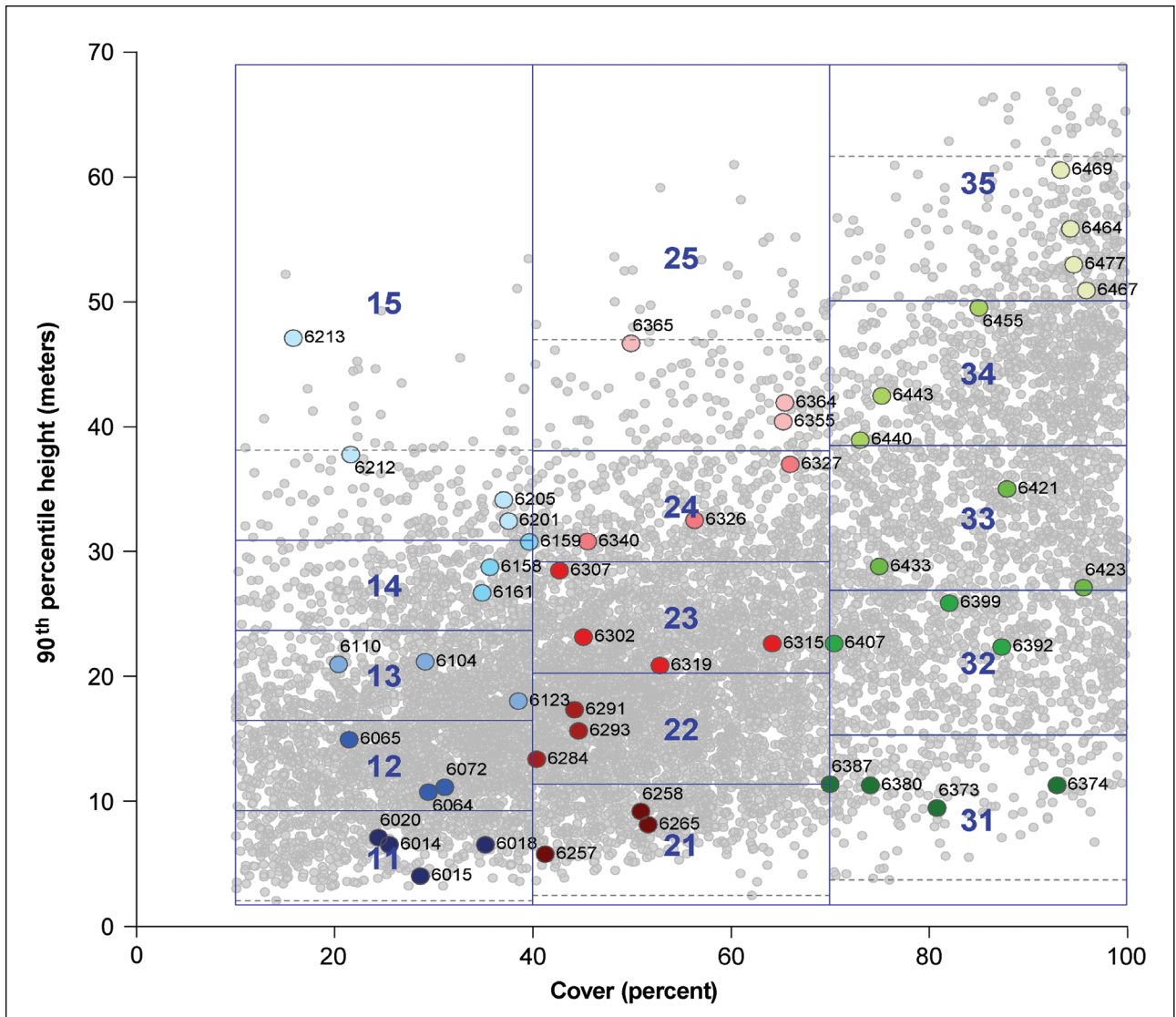


Figure 36—Distribution of sample lidar height (P90) and cover (PC_{1st}) metrics divided into strata for the Oregon study area.

Appendix 2: Strata Boundaries

Table 16—Study area 1: South Carolina

Stratum	Minimum cover	Maximum cover	Minimum height	Maximum height
	----- Percent -----		----- Meters -----	
11	10	40	1.37	6.76
12	10	40	6.76	11.83
13	10	40	11.83	16.89
14	10	40	16.89	21.96
15	10	40	21.96	40
21	40	70	1.37	7.07
22	40	70	7.07	12.29
23	40	70	12.29	17.51
24	40	70	17.51	22.73
25	40	70	22.73	40
31	70	100	1.37	8.05
32	70	100	8.05	13.92
33	70	100	13.92	19.8
34	70	100	19.8	25.67
35	70	100	25.67	40

Table 17—Study area 2: Pennsylvania/New Jersey

Stratum	Minimum cover	Maximum cover	Minimum height	Maximum height
	----- Percent -----		----- Meters -----	
11	10	40	1.37	7.36
12	10	40	7.36	13.14
13	10	40	13.14	18.92
14	10	40	18.92	24.7
15	10	40	24.7	47
21	40	70	1.37	7.71
22	40	70	7.71	13.71
23	40	70	13.71	19.71
24	40	70	19.71	25.71
25	40	70	25.71	47
31	70	100	1.37	9
32	70	100	9	16.14
33	70	100	16.14	23.28
34	70	100	23.28	30.41
35	70	100	30.41	47

Table 18—Study area 3: Maine

Stratum	Minimum cover	Maximum cover	Maximum cover	Maximum height
	----- Percent -----		----- Meters -----	
11	10	40	1.37	5.78
12	10	40	5.78	9.51
13	10	40	9.51	13.23
14	10	40	13.23	16.96
15	10	40	16.96	36
21	40	70	1.37	6.19
22	40	70	6.19	9.71
23	40	70	9.71	13.24
24	40	70	13.24	16.76
25	40	70	16.76	36
31	70	100	1.37	7.31
32	70	100	7.31	11.3
33	70	100	11.3	15.29
34	70	100	15.29	19.28
35	70	100	19.28	36

Table 19—Study area 4: Minnesota

Stratum	Minimum cover	Maximum cover	Minimum height	Maximum height
	----- Percent -----		----- Meters -----	
11	10	40	1.37	5.97
12	10	40	5.97	10.13
13	10	40	10.13	14.29
14	10	40	14.29	18.45
15	10	40	18.45	31
21	40	70	1.37	6.54
22	40	70	6.54	10.84
23	40	70	10.84	15.13
24	40	70	15.13	19.43
25	40	70	19.43	31
31	70	100	1.37	6.94
32	70	100	6.94	11.47
33	70	100	11.47	15.99
34	70	100	15.99	20.52
35	70	100	20.52	31

Table 20—Study area 5: Colorado

Stratum	Minimum cover	Maximum cover	Minimum height	Maximum height
	----- Percent -----		----- Meters -----	
11	10	40	1.37	6.22
12	10	40	6.22	10.72
13	10	40	10.72	15.22
14	10	40	15.22	19.72
15	10	40	19.72	36
21	40	70	1.37	7.28
22	40	70	7.28	12.32
23	40	70	12.32	17.37
24	40	70	17.37	22.41
25	40	70	22.41	36
31	70	100	1.37	7.79
32	70	100	7.79	12.85
33	70	100	12.85	17.91
34	70	100	17.91	22.97
35	70	100	22.97	36

Table 21—Study area 6: Oregon

Stratum	Minimum cover	Maximum cover	Minimum height	Maximum height
	----- Percent -----		----- Meters -----	
11	10	40	1.37	8.96
12	10	40	8.96	16.21
13	10	40	16.21	23.46
14	10	40	23.46	30.72
15	10	40	30.72	69
21	40	70	1.37	11.07
22	40	70	11.07	20.02
23	40	70	20.02	28.98
24	40	70	28.98	37.93
25	40	70	37.93	69
31	70	100	1.37	15.08
32	70	100	15.08	26.78
33	70	100	26.78	38.48
34	70	100	38.48	50.18
35	70	100	50.18	69

Appendix 3: Distribution of Strata by Study Area

Table 22—Study area 1: South Carolina

Stratum	Cell count	Area		
		Square kilometers	Acres	Percentage
NoData	19	0	4	0
0	454	0	101	0
11	21,822	20	4,853	3
12	11,955	11	2,659	1
13	15,772	14	3,508	2
14	18,171	16	4,041	2
15	7,411	7	1,648	1
21	14,469	13	3,218	2
22	13,904	13	3,092	2
23	33,493	30	7,449	4
24	52,887	48	11,762	6
25	19,925	18	4,431	2
31	24,206	22	5,383	3
32	78,949	71	17,558	9
33	204,156	184	45,403	24
34	263,606	237	58,625	30
35	83,290	75	18,523	10

Table 23—Study area 2: Pennsylvania/New Jersey

Stratum	Cell count	Area		
		Square kilometers	Acres	Percentage
0	740	1	165	0
11	9,888	9	2,199	2
12	11,017	10	2,450	2
13	11,698	11	2,602	2
14	7,834	7	1,742	1
15	2,982	3	663	0
21	7,605	7	1,691	1
22	20,152	18	4,482	3
23	32,644	29	7,260	5
24	23,888	21	5,313	4
25	8,703	8	1,936	1
31	11,462	10	2,549	2
32	89,550	81	19,915	14
33	187,580	169	41,717	30
34	160,202	144	35,628	25
35	44,422	40	9,879	7

Table 24—Study area 3: Maine

Stratum	Cell count	Area		
		Square kilometers	Acres	Percentage
11	12,695	11	2,823	1
12	15,238	14	3,389	2
13	13,211	12	2,938	1
14	7,395	7	1,645	1
15	3,993	4	888	0
21	16,421	15	3,652	2
22	33,444	30	7,438	4
23	44,612	40	9,921	5
24	33,593	30	7,471	4
25	15,779	14	3,509	2
31	36,341	33	8,082	4
32	162,586	146	36,158	18
33	236,593	213	52,617	26
34	197,221	177	43,861	22
35	75,010	68	16,682	8

Table 25—Study area 4: Minnesota

Stratum	Cell count	Area		
		Square kilometers	Acres	Percentage
11	63,513	57	14,125	6
12	36,806	33	8,185	4
13	17,942	16	3,990	2
14	8,445	8	1,878	1
15	4,215	4	937	0
21	42,295	38	9,406	4
22	69,724	63	15,506	7
23	50,239	45	11,173	5
24	23,658	21	5,261	2
25	7,381	7	1,641	1
31	40,941	37	9,105	4
32	158,949	143	35,349	16
33	255,127	230	56,739	25
34	179,678	162	39,959	18
35	61,748	56	13,732	6

Table 26—Study area 5: Colorado

Stratum	Cell count	Area		
		Square kilometers	Acres	Percentage
11	145,327	131	32,320	20
12	47,186	42	10,494	7
13	53,540	48	11,907	8
14	41,560	37	9,243	6
15	18,157	16	4,038	3
21	68,078	61	15,140	10
22	40,718	37	9,055	6
23	91,529	82	20,356	13
24	82,924	75	18,442	12
25	26,805	24	5,961	4
31	13,903	13	3,092	2
32	7,951	7	1,768	1
33	28,661	26	6,374	4
34	33,155	30	7,374	5
35	13,140	12	2,922	2

Table 27—Study area 6: Oregon

Stratum	Cell count	Area		
		Square kilometers	Acres	Percentage
0	203	0	45	0
11	52,539	47	11,684	5
12	143,320	129	31,874	12
13	106,117	96	23,600	9
14	46,038	41	10,239	4
15	21,113	19	4,695	2
21	63,283	57	14,074	5
22	185,799	167	41,321	16
23	149,180	134	33,177	13
24	51,977	47	11,559	4
25	17,233	16	3,833	1
31	26,029	23	5,789	2
32	82,633	74	18,377	7
33	96,992	87	21,571	8
34	79,137	71	17,600	7
35	34,699	31	7,717	3

Appendix 4: Examples of Plot Photos for Each Study Area



Figure 37—(A) Example of mixed hardwood forest in South Carolina; (B) example of bald cypress (*Taxodium distichum*) forest in South Carolina.



Figure 38—(A) Example of New Jersey pine barrens forest; (B) example of mixed-hardwood forest in Pennsylvania.



Figure 39—(A) Example of mixed-conifer forest in Maine; (B) example of mixed-hardwood forest in Maine.



Figure 40—(A) Examples of tamarack (*Larix laricina*) and black spruce (*Picea mariana*) forest in Minnesota; (B) example of mixed-hardwood forest in Minnesota.



Figure 41—(A) Example of quaking aspen (*Populus tremuloides*) forest in Colorado; (B) example of forest containing woodland species in Colorado.

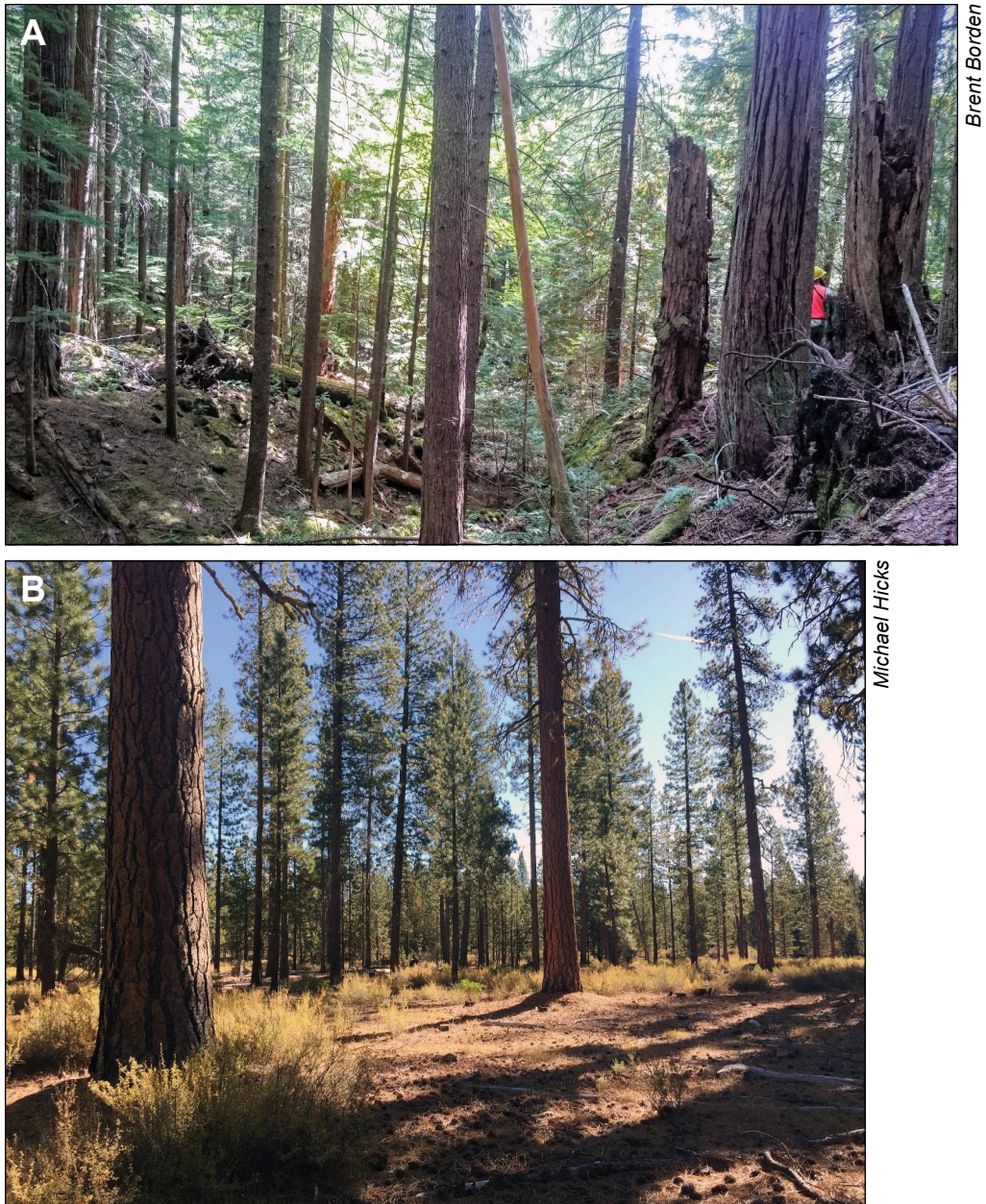


Figure 42—(A) Example of mixed-conifer forest in western Oregon; (B) example of mixed-pine forest in eastern Oregon

Appendix 5: Forest Inventory and Analysis Tree Species Encountered by Field Crews

FIA code	USDA PLANTS code	Scientific name	Common name
11	ABAM	<i>Abies amabilis</i> (Dougl. ex Loud.) Dougl. ex Forbes	Pacific silver fir
12	ABBA	<i>Abies balsamea</i> (L.) Mill.	balsam fir
17	ABGR	<i>Abies grandis</i> (Dougl. ex D. Don) Lindl.	grand fir
19	ABLA	<i>Abies lasiocarpa</i> (Hook.) Nutt.	subalpine fir
21	ABSH	<i>Abies shastensis</i> A. Murray bis var. <i>shastensis</i> Lemmon	Shasta red fir
22	ABPR	<i>Abies procera</i> Rehder	noble fir
43	CHTH2	<i>Chamaecyparis thyoides</i> (L.) Britton, Sterns & Poggenb.	Atlantic white cedar
65	JUOS	<i>Juniperus osteosperma</i> (Torr.) Little	Utah juniper
66	JUSC2	<i>Juniperus scopulorum</i> Sarg.	Rocky Mountain juniper
68	JUVI	<i>Juniperus virginiana</i> L.	eastern redcedar
71	LALA	<i>Larix laricina</i> (Du Roi) K. Koch	tamarack
81	CADE27	<i>Calocedrus decurrens</i> (Torr.) Florin	incense-cedar
91	PIAB	<i>Picea abies</i> (L.) Karst.	Norway spruce
93	PIEN	<i>Picea engelmannii</i> Parry ex Engelm.	Engelmann spruce
94	PIGL	<i>Picea glauca</i> (Moench) Voss	white spruce
95	PIMA	<i>Picea mariana</i> (Mill.) Britton, Sterns & Poggenb.	black spruce
96	PIPU	<i>Picea pungens</i> Englem.	blue spruce
97	PIRU	<i>Picea rubens</i> Sarg.	red spruce
105	PIBA2	<i>Pinus banksiana</i> Lamb.	jack pine
106	PIED	<i>Pinus edulis</i> Englem.	Common pinyon, two-needle pinyon
108	PICO	<i>Pinus contorta</i> Dougl. ex Loud.	lodgepole pine
110	PIEC2	<i>Pinus echinata</i> Mill.	shortleaf pine
113	PIFL2	<i>Pinus flexilis</i> James	limber pine
119	PIMO3	<i>Pinus monticola</i> Douglas ex D. Don	western white pine
121	PIPA2	<i>Pinus palustris</i> Mill.	longleaf pine
122	PIPO	<i>Pinus ponderosa</i> Lawson & C. Lawson	ponderosa pine
125	PIRE	<i>Pinus resinosa</i> Aiton	red pine
126	PIRI	<i>Pinus rigida</i> Mill.	pitch pine
128	PISE	<i>Pinus serotina</i> Michx.	pond pine
129	PIST	<i>Pinus strobus</i> L.	eastern white pine
131	PITA	<i>Pinus taeda</i> L.	loblolly pine
132	PIVI2	<i>Pinus virginiana</i> Mill.	Virginia pine
202	PSME	<i>Pseudotsuga menziesii</i> (Mirb.) Franco	Douglas-fir
221	TADI2	<i>Taxodium distichum</i> (L.) Rich.	bald cypress
222	TAAS	<i>Taxodium ascendens</i> Brongn.	pond cypress
241	THOC2	<i>Thuja occidentalis</i> L.	arborvitae
242	THPL	<i>Thuja plicata</i> Donn ex D. Don	western redcedar

FIA code	USDA PLANTS code	Scientific name	Common name
261	TSCA	<i>Tsuga canadensis</i> (L.) Carrière	eastern hemlock
263	TSHE	<i>Tsuga heterophylla</i> (Raf.) Sarg.	western hemlock
264	TSME	<i>Tsuga mertensiana</i> (Bong.) Carr.	mountain hemlock
312	ACMA3	<i>Acer macrophyllum</i> Pursh	bigleaf maple
315	ACPE	<i>Acer pensylvanicum</i> L.	striped maple
316	ACRU	<i>Acer rubrum</i> L.	red maple
317	ACSA2	<i>Acer saccharinum</i> L.	silver maple
318	ACSA3	<i>Acer saccharum</i> Marshall var. <i>schneckii</i> Rehder	sugar maple
319	ACSP2	<i>Acer spicatum</i> Lam.	mountain maple
320	ACPL	<i>Acer platanoides</i> L.	Norway maple
350	ALNUS	<i>Alnus</i> Mill sp.	alder
361	ARME	<i>Arbutus menziesii</i> Pursh	Pacific madrone
370	BETUL	<i>Betula</i> L. sp.	birch
371	BEAL2	<i>Betula alleghaniensis</i> Britton	yellow birch
372	BELE	<i>Betula lenta</i> L.	sweet birch
375	BEPA	<i>Betula papyrifera</i> Marshall	paper birch
391	CACA18	<i>Carpinus caroliniana</i> Walter	American hornbeam, musclewood
401	CAAQ2	<i>Carya aquatica</i> (Michx. f.) Nutt.	water hickory
402	CACO15	<i>Carya cordiformis</i> (Wangenh.) K. Koch	bitternut hickory
403	CAGL8	<i>Carya glabra</i> (Mill.) Sweet	pignut hickory
407	CAOV2	<i>Carya ovata</i> (Mill.) K. Koch	shagbark hickory
409	CAAL27	<i>Carya alba</i> (L.) Nutt., nom. utique rej.	mockernut hickory
431	CHCHC4	<i>Chrysolepis chrysophylla</i> (Douglas ex Hook.) Hjelmqvist var. <i>chrysophylla</i>	giant chinkapin, golden chinkapin
461	CELA	<i>Celtis laevigata</i> Willd.	sugarberry
491	COFL2	<i>Cornus florida</i> L.	flowering dogwood
492	CONU4	<i>Cornus nuttallii</i> Audubon ex Torr. & A. Gray	Pacific dogwood
521	DIVI5	<i>Diospyros virginiana</i> L.	common persimmon
531	FAGR	<i>Fagus grandifolia</i> Ehrh.	American beech
541	FRAM2	<i>Fraxinus americana</i> L.	white ash
543	FRNI	<i>Fraxinus nigra</i> Marshall	black ash
591	ILOP	<i>Ilex opaca</i> Aiton	American holly
602	JUNI	<i>Juglans nigra</i> L.	black walnut
611	LIST2	<i>Liquidambar styraciflua</i> L.	sweetgum
621	LITU	<i>Liriodendron tulipifera</i> L.	tuliptree
653	MAVI2	<i>Magnolia virginiana</i> L.	sweetbay
682	MORU2	<i>Morus rubra</i> L.	red mulberry
693	NYSY	<i>Nyssa sylvatica</i> Marshall	blackgum
701	OSVI	<i>Ostrya virginiana</i> (Mill.) K. Koch var. <i>virginiana</i>	eastern hophornbeam

FIA code	USDA PLANTS code	Scientific name	Common name
721	PEBO	<i>Persea borbonia</i> (L.) Spreng.	redbay
741	POBA2	<i>Populus balsamifera</i> L.	balsam poplar
742	PODE3	<i>Populus deltoides</i> W. Bartram ex Marshall	eastern cottonwood
743	POGR4	<i>Populus grandidentata</i> Michx.	bigtooth aspen
746	POTR5	<i>Populus tremuloides</i> Michx.	quaking aspen
761	PRPE2	<i>Prunus pensylvanica</i> L. f.	pin cherry
762	PRSE2	<i>Prunus serotina</i> Ehrh.	black cherry
763	PRVI	<i>Prunus virginiana</i> L.	common chokecherry
800	QUERC	<i>Quercus</i> L. sp.	oak
802	QUAL	<i>Quercus alba</i> L.	white oak
806	QUCO2	<i>Quercus coccinea</i> Münchh.	scarlet oak
812	QUFA	<i>Quercus falcata</i> Michx.	southern red oak
813	QUPA5	<i>Quercus pagoda</i> Raf.	cherrybark oak
814	QUGA	<i>Quercus gambelii</i> Nutt.	Gambel oak
816	QUIL	<i>Quercus ilicifolia</i> Wangenh.	bear oak
820	QULA3	<i>Quercus laurifolia</i> Michx.	laurel oak
824	QUMA3	<i>Quercus marilandica</i> Münchh.	blackjack oak
825	QUMI	<i>Quercus michauxii</i> Nutt.	swamp chestnut oak
827	QUNI	<i>Quercus nigra</i> L.	water oak
830	QUPA2	<i>Quercus palustris</i> Münchh.	pin oak
831	QUPH	<i>Quercus phellos</i> L.	willow oak
832	QUPR2	<i>Quercus montana</i> Willd.	chestnut oak
833	QURU	<i>Quercus rubra</i> L.	northern red oak
835	QUST	<i>Quercus stellata</i> Wangenh.	post oak
837	QUVE	<i>Quercus velutina</i> Lam.	black oak
838	QUVI	<i>Quercus virginiana</i> Mill.	live oak
921	SAAM2	<i>Salix amygdaloides</i> Andersson	peachleaf willow
923	SABE2	<i>Salix bebbiana</i> Sarg.	Bebb willow
925	SACA5	<i>Salix caroliniana</i> Michx.	coastal plain willow
931	SAAL5	<i>Sassafras albidum</i> (Nutt.) Nees	sassafras
951	TIAM	<i>Tilia americana</i> L.	American basswood
971	ULAL	<i>Ulmus alata</i> Michx.	winged elm
972	ULAM	<i>Ulmus americana</i> L.	American elm
975	ULRU	<i>Ulmus rubra</i> Muhl.	slippery elm
994	TRSE6	<i>Triadica sebifera</i> (L.) Small	Chinese tallow

Source: USDA PLANTS database (USDA NRCS 2019). FIA = Forest Inventory and Analysis.

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