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MÁSTER EN INGENIERÍA DE MONTES

Development of tree height prediction models for the United States Pacific Coast States

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A Vicente, por su inestimable ayuda en lo académico y en lo no académico.

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1. ABSTRACT

A good forest management planning requires reliable projections of growth, so it is necessary to have an inventory as accurate as possible. When it is wanted to perform the measurement of different variable of a tree, some of them like height, it can be more difficult to measure than others like diameter. In addition, some species have the added complication that it height can exceed 300 feet, such as, for example, the Redwoods, in the Pacific Coast of the United States. Therefore, to estimate them from other variables simplest to measure is an advantage.

The United States Forest Inventory has taken this advantage, and from the second measurement began to measure only a sample of the heights and estimate the rest.

Several studies dedicated to creating height-diameter equations in a lot of areas and species, with which estimate the heights from the diameter, and even adding more variables. Generally, researchers have focused on developing these equations for abundant or more important species, so, in this study, has been treated to make equations height-diameter for all species listed in the inventory of the Pacific Coast of the Unites States.

To perform these equations we used mixed models since they increase the prediction accuracy and improve results significantly. We used Chapman-Richards equation for adjustment. This equation has already been used by others researchers for this purpose because it fit very well to growth of trees.

We have obtained a total of 61 equations for the species of the Pacific Coast, and the results shows that these have a good fit and the convenience of using these models.

1. RESUMEN

Una buena planificación del manejo forestal requiere proyecciones confiables de crecimiento, para ello es necesario tener un inventario lo más preciso posible. Cuando se quiere llevar a cabo la medición de distintas variables de un árbol, algunas de ellas como la altura, pueden resultar bastante más complicadas de medir que otras como el diámetro. Además, algunas especies tienen la complicación añadida de que su altura puede superar los 90 metros, como es el caso de, por ejemplo, las Sequoias en la Costa del Pacífico de los Estados Unidos. Por ello, poder estimarlas a partir de otras variables más sencillas de medir resulta una ventaja.

El Inventario Forestal de Estados Unidos se ha aprovechado de esta ventaja y a partir de su segunda medición empezó a medir solamente una muestra de las alturas y estimar el resto.

Son numerosos los estudios dedicados a la creación de ecuaciones altura-diámetro en diversas zonas y especies, con las que poder estimar las alturas a partir del diámetro, e incluso añadiendo más variables. Generalmente los investigadores se han centrado en desarrollar estas ecuaciones para las especies más abundantes o de mayor importancia, por ello en este estudio se ha tratado de realizar ecuaciones altura-diámetro para todas las especies recogidas en el inventario de la Costa del Pacífico de los Estados Unidos.

Para realizar estas ecuaciones hemos utilizado modelos mixtos puesto que aumentan la precisión de la predicción y mejoran los resultados de forma muy significativa. Se ha utilizado la ecuación de Chapman-Richards para el ajuste, ya utilizada por otros autores con este fin puesto que se ajusta muy bien al crecimiento de los árboles.

Hemos obtenido un total de 61 ecuaciones para las especies de la Costa del Pacífico, y los resultados han mostrado que estas presentan un buen ajuste y la conveniencia de utilizar estos modelos.

2. INTRODUCTION

Height is a variable costly to measure, and, as a result, trees are frequently subsampled for height. Foresters often choose to measure only a few trees' heights and estimate the remaining with height-diameter equations. Foresters can also use height-diameter equations to indirectly estimate height growth by applying the equations to a sequence of diameters that were either measured directly in a continuous inventory or predicted indirectly by a diameter-growth equation (Hanus et al, 1999). Due to that, several inventories measure all the diameters of the trees and only a sample of the heights.

The first United States Forest Inventory and Analysis (FIA) started in 1930 and measured the heights of all trees in each plot, but, in the second measurement, it was decided to sample the heights. To choose the subsample, it was selected one tree for each diameter class in each plot. Having a complete cycle of measurements, we could fit the models to predict the height of the trees that were not sampled. An advantage is that the sample is from the complete region, so all the species and situations are represented.

There are some preliminary researches which cover this topic; Garman et al (1995) developed asymtotic height-diameter equations for twenty-four species in western Oregon, later, Hanus et al (1999) developed height-diameter equations for species in the coastal regions of the Pacific Northwest. Monleon (2003) compared model forms currently used in forestry with hierarchical lineal models that account explicitly for the clustered structure of the data and Temesgen et al (2008) examined and compared different tree height prediction strategies for Douglas-fir forest in southwest Oregon.

In this study we will develop height-diameter equations for all common and representative species in California, Oregon and Washington from the United States FIA database.

3. OBJETIVES

Develop height-diameter equations for tree species of California, Oregon and Washington which will able to estimate the height from a measured diameter.

4. MATERIAL AND METHODS

4.1 STUDY AREA

The study includes all forestlands in California, Oregon and Washington (Figure 1), an environmentally diverse and floristically rich region. Latitude ranges from 32° 32’ to 49° N, spanning 1150 miles (mi) (see Appendix IV. Metric Equivalents). Elevation ranges from 282 feet (ft) below to 14505 ft above sea level. Total land area is 371797 square miles (sq mi), of which an estimated 133228 sq miis forestland. The study area includes 19 ecoregions and many distinct forest types, including warm and cold deserts, semi-arid woodlands, montane and high elevation forests, and temperate rain forests. Approximately 13% of the forest land is in reserved areas. Management regimens vary widely, from wilderness areas to intensively managed, short-rotation plantations (Monleon and Lintz, 2015).

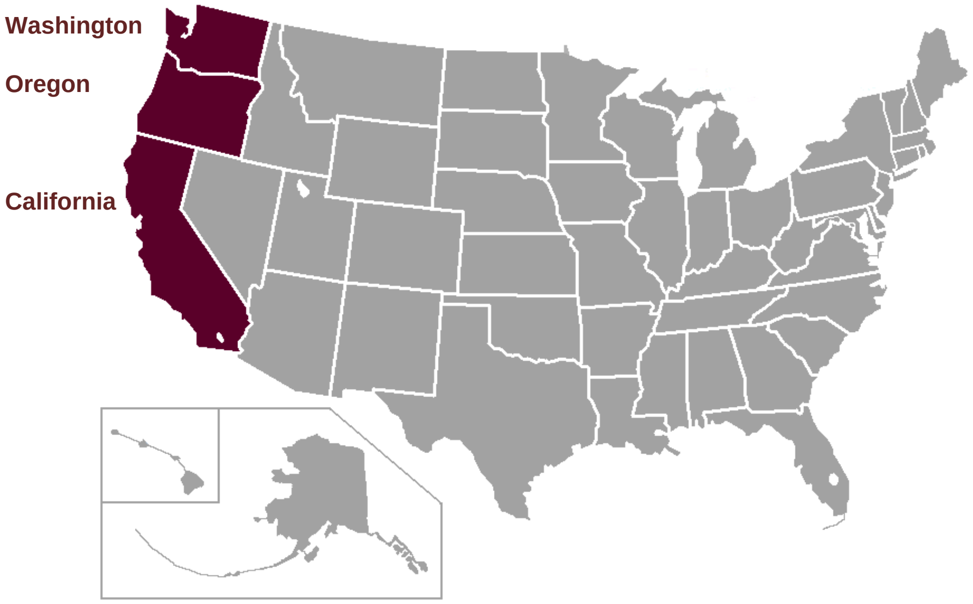


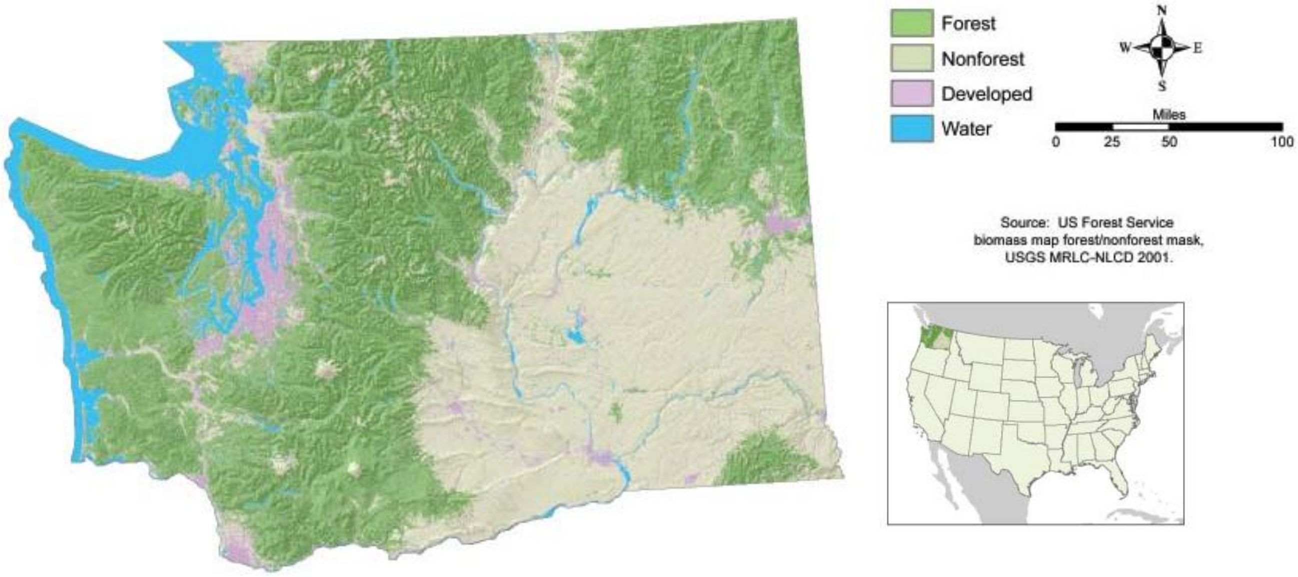
Figure 1. Pacific Coast States for which the equations have been developed

More than half of Washington is forested. About 22 million acres of forest cover the total land area of 43 million acres, almost evenly divided between east and west of the Cascade crest. Washington is a leading lumber producer, rich in stands of Douglas fir, hemlock, ponderosa and white pine, and cedar. This state has deep temperate rainforests in the west, mountain ranges in the west, central, northeast and far southeast, and a semi-arid basin region in the east, central and south, given over to intensive agriculture. Total land area is 71362 sq mi. Latitude ranges from 45°33′ N to 49° N, and longitude ranges from 116°55′ W to 124°46′ W. The highest point is Mount Rainier, with14410 ft., the lowest point is the Pacific Ocean sea level.

About 86 percent of Washington’s forests are dominated by coniferous forest types, predominantly Douglas-fir (39 percent of all forested land area), fir/spruce/mountain hemlock (18 percent), and western hemlock / Sitka spruce (15 percent). Hardwood forest types cover an additional 2.6 million acres (12 percent of forested land area). The major hardwood forest type is alder/maple (1.9 million acres) (USDA, Forest Service, Pacific Northwest Research Station).

Washington has approximately 95 billion net cubic feet (413 billion board feet) of wood volume on forest land with a mean volume of about 4,231 cubic feet (18,433 board feet) per acre. The greatest proportion of wood volume is found in softwood tree species such as Douglas-fir, true firs, and western hemlock, which collectively make up 73 percent of all live-tree volume on Washington forest land. Total estimated biomass in live trees and dead wood across Washington is 107 tons per acre (USDA, Forest Service, Pacific Northwest Research Station).

The federal government manages about 44 percent of Washington’s 22.4 million acres of forested land. The National Forest System (NFS) and the National Park Service (NPS) administer most of this acreage. The state also has substantial holdings, mostly managed by the Washington Department of Natural Resources with about 2.5 million acres (USDA, Forest Service, Pacific Northwest Research Station).



Source: US Forest Service biomass map forest/nonforest mask, USGS MRLC-NLCD 2001.

Figure 2. Physical map of Washington

Almost half of Oregon's, 61-million-acres of land area (30 million acres), is forested. Oregon’s landscape is so diverse, with a windswept Pacific coastline, a volcano studded Cascade Range, abundant bodies of water in and west of the Cascades, dense evergreen, mixed, and deciduous forest at lower elevations, and a high desert of its east. Total land area is 98466 sq mi. Latitude ranges from 42° N to 46° 18’ N, and longitude ranges from 116°28′ W to 124°38′ W. The highest point is Mount Hood, with11249.3 ft., the lowest point is the Pacific Ocean sea level. The close proximity to the Pacific Ocean results in mild temperatures and high precipitation in the Coast Range, resulting in excellent growing conditions.

About 86 percent of Oregon’s forests are dominated by coniferous forest types, predominantly Douglas-fir (35 percent of all forested land area), ponderosa pine (16 percent), and fir/spruce/mountain hemlock (12 percent). Hardwood forest types cover an additional 3 million acres (12 percent of forested land area). The major hardwood forest types are alder/maple (1.2 million acres), western oak (800,000 acres), and tanoak/laurel (600,000 acres) (USDA, Forest Service, Pacific Northwest Research Station).

Oregon has approximately 100 billion net cubic feet (433 billion board feet) of wood volume on forest land with a mean volume of about 3,322 cubic feet (14,204 board feet) per acre. The greatest proportion of wood volume is found in commercially important softwood tree species such as Douglas-fir, true firs, pines, and western hemlock, which collectively make up 93 percent of all live-tree volume on Oregon forest land (USDA, Forest Service, Pacific Northwest Research Station).

Total estimated biomass in live trees and dead wood across Oregon is 2.7 billion tons. There is almost three times as much biomass in live trees compared to dead trees. Over 2 billion tons of biomass and 1 billion tons of carbon have accumulated in live trees (equal to or greater than 1 inch diameter at breast height), primarily on US Forest Service land (56 percent). Softwood forest types have 10 times the amount of biomass and carbon as hardwood types (USDA, Forest Service, Pacific Northwest Research Station).

Douglas-fir is the most abundant tree species in Oregon, and therefore contributes the most to biomass and carbon storage. The more than 1 billion tons of Douglas-fir biomass represents about 573 million tons of carbon sequestered in live trees (USDA, Forest Service, Pacific Northwest Research Station).

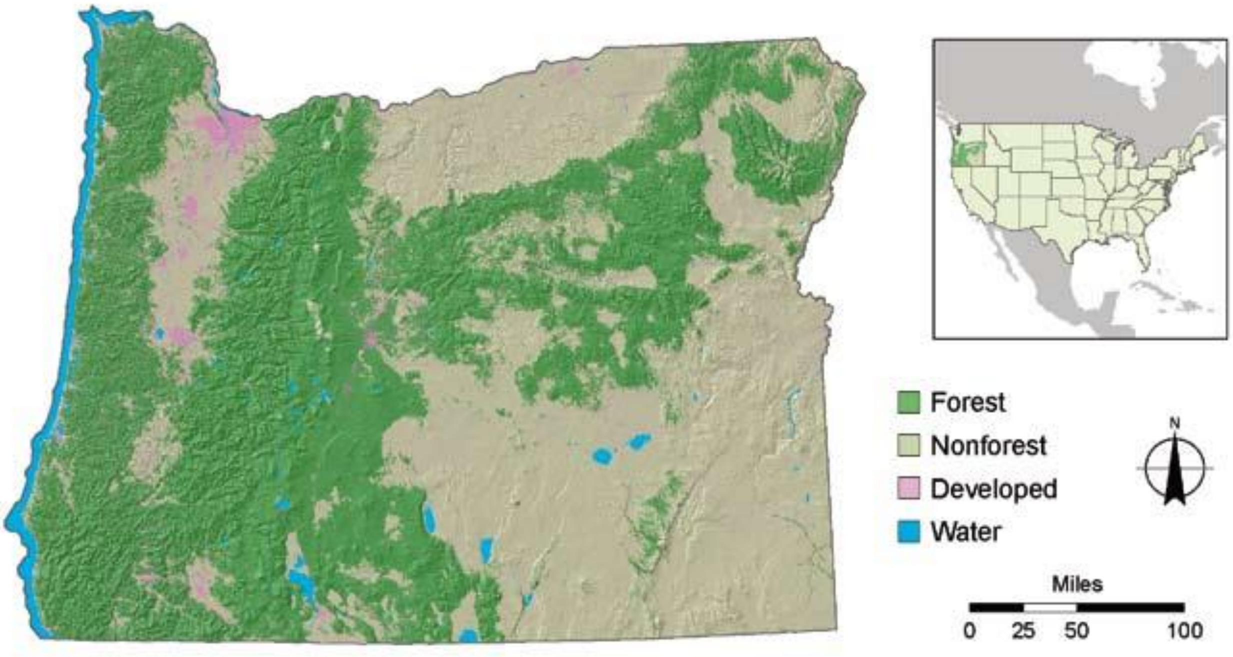


Figure 3. Physical map of Oregon

California is the most populous U.S. State and the third largest by area, with 163695 sq mi. California's diverse geography ranges from the Sierra Nevada in the east to the Pacific Coast in the west, from the Redwood-Douglas fir forests of the northwest, to the Mojave Desert areas in the southeast. The center of the state is dominated by the Central Valley, a major agricultural area. Latitude ranges from 32°32′ N to 42° N, and longitude ranges from 114°8′ W to 124°26′ W. The highest point is Mount Whitney, with14504 ft., and the lowest point is Badwater Basin in Death Valley, with -282 ft.

Forests cover about a third of the state's 100 million acres, and most of this forest (19 million acres) is publicly managed. Roughly 2 million acres are reserved in wilderness areas and state and national parks. More than half (about 57 percent) of California's forests are softwood conifer types, totaling 19 million acres. Over 40 percent are classified in the California mixed-conifer group (8 million acres) (USDA, Forest Service, Pacific Northwest Research Station).

There are approximately 95 billion net cubic feet (428 billion Scribner board feet) of wood volume on forest land, with a mean volume of about 2,875 cubic feet (12,879 Scribner board feet) per acre (USDA, Forest Service, Pacific Northwest Research Station).

The greatest proportion is from softwood tree species such as Douglas-fir, true firs, and pines, which collectively make up 81 percent of net live-tree volume. The remaining 19 percent of live-tree volume is from hardwood species (USDA, Forest Service, Pacific Northwest Research Station).

Over 2 billion tons of biomass and 1 billion tons of carbon have accumulated in live trees (=1 inch diameter at breast height), primarily on unreserved forest land. The majority of this biomass (51 percent) is on Forest Service land; 24 percent of that is on reserved land. Live trees on timberland contain about 1.5 billion tons of biomass and 786 million tons of carbon. Softwood forest types have double the amount of biomass and carbon of hardwood types, with biomass estimates ranging from a low of 4 million tons in the western hemlock/Sitka spruce type to a high of 724 million tons in the mixed-conifer type. On average, we estimated that the total biomass of live trees, snags, and coarse woody material was about 78 tons per acre across the state, which represents a carbon mass of about 40 tons per acre (USDA, Forest Service, Pacific Northwest Research Station).

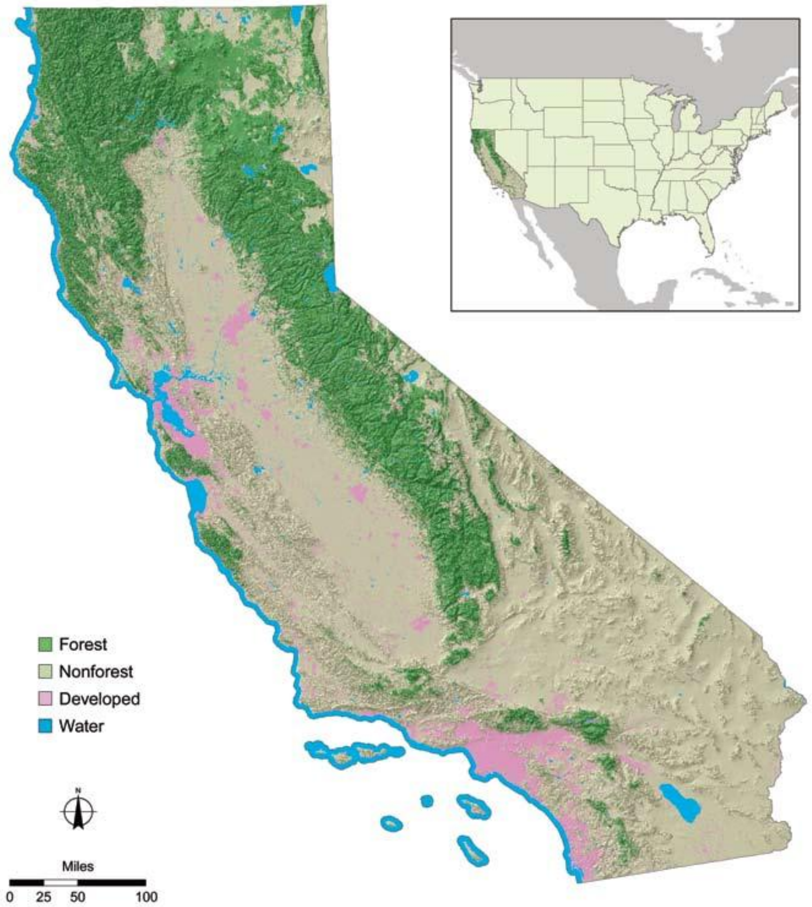


Figure 4. Physical map of California

4.2. THE INVENTORY OF WASHINGTON, OREGON AND CALIFORNIA

For this study we used the data collected in the Forest Inventory conducted by the USDA Forest Service (United States Department of Agriculture Forest Service).

The national Forest Inventory and Analysis (FIA) program consists of three phases. Phase 1 is a remote sensing phase aimed at classifying all land into forest and non forest. Phase 2 consists of a set of field sample locations distributed across the landscape with one sample location for every 24 km^2 approximately (6000 acres), at standard intensification. This spatially balanced sample is divided into 10 spatially balanced panels, which are measured one each year. In plots which belong to forest service, the density of the sample is increased by 3. Forested sample locations are visited by field crews that collect a variety of forest ecosystem data. Non forest locations are visited, as necessary, to quantify rates of land use change or to measure regional data items. Phase 3 consists of a subset of the phase 2 plots (approximately one every 389 km^2, 96000 acres), which are visited during the growing season in order to collect an extended suite of ecological data including full vegetation census, tree and crown condition, soil data, lichen diversity, coarse woody material, and ozone injury (USDA Forest Service, 2015).

Pacific Northwest FIA reports on the status and trends of forests in Alaska, Washington, Oregon, California, Hawaii and the Pacific Islands, and provides information sought by resource planners, policy analysts, and others involved in forest resource decision-making. Data collected in PNW-FIA inventories are summarized, interpreted, analyzed, and published in analytical reports and research articles of national, state, regional, and sub-regional scope. Information is presented by forest land and owner classes for land use change; timber volume, growth, mortality, and removals; potential forest productivity; opportunities for silvicultural treatment; and type and area of wildlife habitats. The data collected in these inventories represent a wealth of information that can answer questions about the status and trend of forest ecosystems, distribution of plant species and their relationship to the environment, the incidence of insects and disease in relation to forest type and condition, changes in forest structure and productivity resulting from disturbance, and improved (USDA Forest Service, 2015).

4.2.1 PLOT DESIGN GENERAL DESCRIPTION

The Core ground plot consists of four subplots approximately 170 m^2 (1/24 acres) in size with a radius of 7.3 m (24 feet horizontal). The center subplot is subplot 1. Subplots 2, 3, and 4 are located 36.6 m^2 (120 feet horizontal) at azimuths of 360, 120, and 240 degrees, respectively, from the center of subplot 1 (Figure 2: FIA Phase 2 plot diagram). Field plots also include macroplots that are 1012 m^2 (¼ acres) in size with a radius of 17.95 m (58.9 feet horizontal) l; each macroplot center coincides with the subplot's center. Macroplots are numbered in the same way as subplots. Throughout this field guide, the use of the word 'plot' refers to the entire set of four subplots/macroplots. 'Plot center' is defined as the center of subplot 1. Each subplot contains a microplot of approximately 13 m^2 (1/300 acres) in size with a radius of 2 m (6.8 feet horizontal). The center of the microplot is offset 90 degrees and 3.7 m (12.0 feet horizontal) from each subplot center. Microplots are numbered in the same way as subplots. In the PNW-FIA annual inventory, the four subplots/macroplots are laid out in the pattern shown in Figure 2; subplots are never "substituted" or "moved" in order to keep the entire subplot/macroplot within a homogeneous condition (USDA Forest Service, 2015).

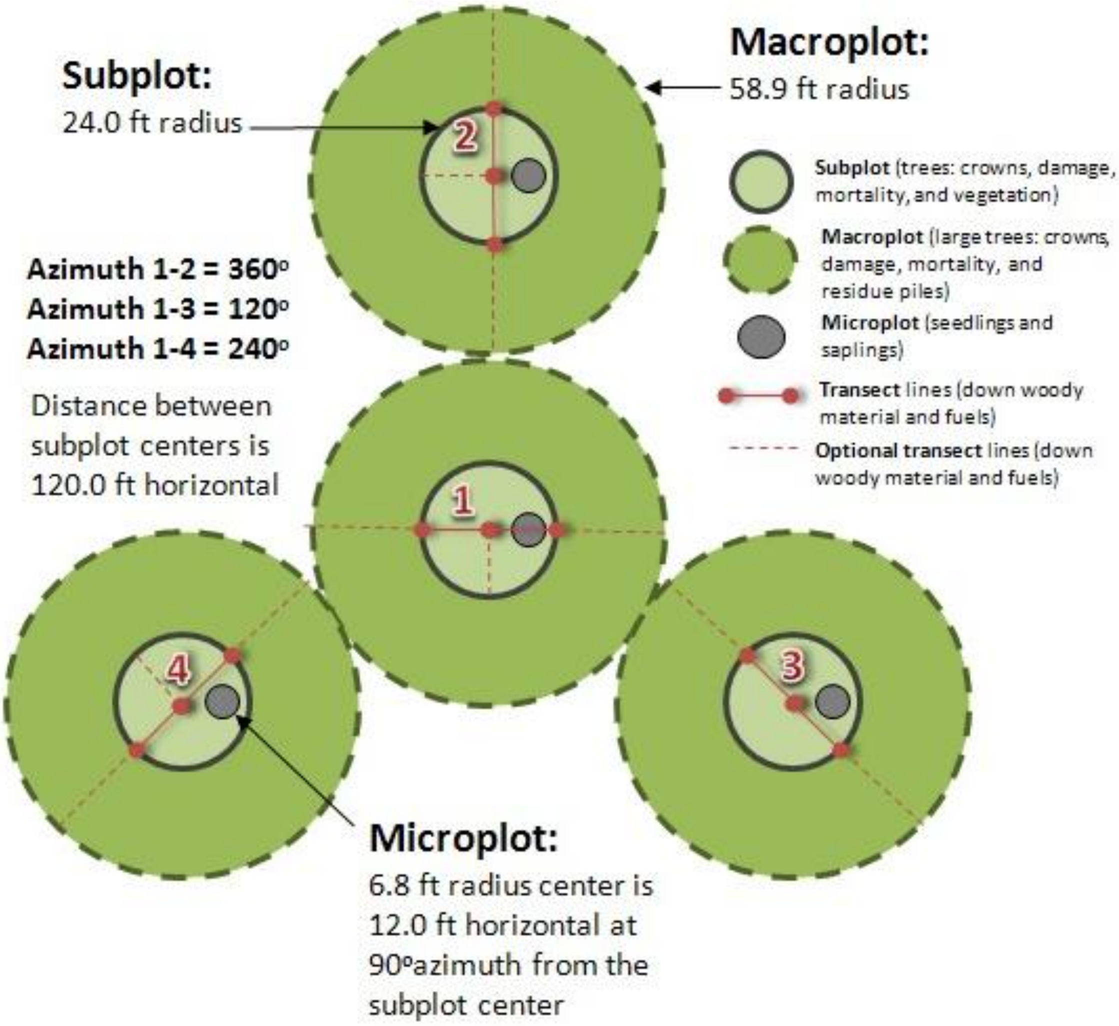


Figure 5. FIA Phase 2 plot diagram (USDA Forest Service, 2015)

On remeasurement plots, tree lengths and crown measurements will be measured on a subset of macroplot trees to improve field efficiency. Lengths of normally-formed trees (total length) can be estimated well with regression models when an appropriate subsample of trees are measured on a plot. The live trees for which total length and actual length must be measured will be identified systematically on the plot, by condition, species, and diameter class, and are called Growth Sample Trees (GST) (USDA Forest Service, 2015).

In addition to GSTs, all live or dead trees with observed broken tops will have total length and actual length measured or estimated in the field. Dead trees with intact tops do not need to be measured. Trees previously coded as having a broken top will have the broken-top damage code pre-populated for the current measurement (USDA Forest Service, 2015).

Code that identifies whether the tree is to be measured for total length and actual length. All live trees and saplings within the subplot will automatically be assigned Growth Sample Tree. In the order of tally on the macroplot (starting from north on each subplot) the first live tree of a species encountered in each Diameter at Breast Height (DBH) group (Table 1) and condition class will be identified as a growth sample tree. Growth sample trees are systematically identified even if the tree is damaged or unhealthy; trees with unbroken tops are selected preferentially. Growth sample trees will be assigned by the data recorder. If a previously-identified tree has died, it no longer qualifies as a growth sample tree and a replacement must be found if present. Other changes (e.g., condition class, species, previous diameter, or horizontal distance) do not affect pre-identified growth sample trees (USDA Forest Service, 2015).

Table 1. DBH Groups

DBH Groups	
Inches	**Centimeter**
1.0 to 4.9	2.5 to 12.5
5.0 to 9.9	12.6 to 25.2
10.0 to 14.9	25.3 to 37.9
15.0 to 19.9	38 to 50.6
20.0 to 24.9	50.7 to 63.3
25.0 to 29.9	63.4 to 76
30.0 to 39.9	76.1 to 101.4
>=40	>=101.5

Diameters are measured at either breast height (DBH) or at the root collar (DRC). Species requiring DRC, referred to as woodland species. Trees with diameters between 1.0- and 4.9-inches are measured on the 6.8-foot radius microplot, those with diameters of 5.0-inches and larger are measured on the 24-foot radius subplots.

Additional trees, with diameter breakpoints defined by region, are measured on the macroplot. Diameters are used in calculating volume, growth, average stand diameter, and stocking-related estimates such as forest type and stand size (USDA Forest Service, 2015).

Species that requiring diameter at the root collar the diameter is measured at the ground line or at the stem root collar, whichever is higher. For these trees, treat clumps of stems having a unified crown and common root stock as a single tree (USDA Forest Service, 2015).

4.3 DATABASE

Our database includes a complete cycle of inventory, 10 years, from 2004 to 2013. The total database contains 21733 plots, 76 species and 613597 trees.

The table 2 shows the maximum and minimum values of diameters and heights by specie. The diameter is measured in inches and the height in feet. The maximum values of diameter, 157.6 inches (400.3 cm) and height, 309 feet (94.2 m) are from *Sequoia sempervirens.* The minimum values are 1 inch (2.5 cm), the minimum diameter measured, and 1 foot (0.3 m).

Table 2. Maximum and minimum values of diameter and height for specie

Specie	Common Name	Code SPP	DIA max	DIA min	h max	h min
Abies amabilis	Pacific silver fir	ABAM	91.0	1.0	227	5
Abies concolor & grandis, CA	White / grand fir, CA	ABCO, CA	66.0	1.0	210	5
Abies concolor & grandis, W OR&WA	White / grand fir, W OR&WA	ABCO, W OR&A	62.5	1.0	225	6
Abies concolor & grandis, E OR&WA	White / grand fir, E OR&WA	ABCO, E OR&A	68.0	1.0	205	5
Abies lasiocarpa	Subalpine fir	ABLA	53.8	1.0	145	5
Abies magnifica	Red fir	ABMA	93.3	1.0	220	5
Abies procera	Noble fir	ABPR	83.6	1.0	248	5
Chamaecyparis lawsoniana	Port-Orford-cedar	CHLA	61.1	1.0	188	6
Chamaecyparis nootkatensis	Alaska yellow-cedar	CHNO	95.4	1.0	185	5
Cupressus spp.	Cypress	Cupressus	25.7	1.0	57	6
Juniperus californica	California juniper	JUCA	45.9	1.0	47	2
Juniperus occidentalis	Western juniper	JUOC	103.1	1.0	95	6
Juniperus osteosperma	Utah juniper	JUOS	55.3	1.2	35	3
Larix lyallii	Subalpine larch	LALI	38.4	1.0	108	7

Table 2 (continuation). Maximum and minimum values of diameter and height for specie

Specie	Common Name	Code SPP	DIA max	DIA min	h max	h min
Larix occidentalis	Western larch	LAOC	89.9	1.0	180	5
Calocedrus decurrens	Incense-cedar	CADE	89.9	1.0	226	5
Picea breweriana	Brewer spruce	PIBR	35.0	1.1	125	8
Picea engelmannii	Engelmann spruce	PIEN	50.5	1.0	194	5
Picea sitchensis	Sitka spruce	PISI	93.4	1.0	260	8
Pinus albicaulis, CA	Whitebark pine, CA	PIAL CA	42.2	1.0	74	5
Pinus albicaulis, OR&WA	Whitebark pine, OR&WA	PIAL OR&WA	45.3	1.0	78	5
Pinus attenuata	Knobcone pine	PIAT	52.8	1.0	131	7
Pinus balfouriana	Foxtail pine	PIBA	63.0	5.0	102	10
Pinus contorta, CA	Lodgepole pine, CA	PICO CA	58.4	1.0	177	5
Pinus contorta, OR&WA	Lodgepole pine, OR&WA	PICO OR&WA	83.0	1.0	132	5
Pinus contorta var. contorta	Shore pine	PICO Coast	25.5	1.0	111	9
Pinus coulteri	Coulter pine	PICOUL	38.3	1.0	122	7
Pinus flexilis	Limber pine	PIFL	72.1	1.0	121	8
Pinus jeffreyi	Jeffrey pine	PIJE	78.8	1.0	211	5
Pinus lambertiana	Sugar pine	PILA	80.0	1.0	248	6
Pinus monticola	Western white pine	PIMO	77.4	1.0	220	5
Pinus muricata	Bishop pine	PIMU	38.8	4.4	151	23
Pinus ponderosa, CA	Ponderosa pine, CA	PIPO CA	69.6	1.0	226	6
Pinus ponderosa, W OR&WA	Ponderosa pine, W OR&WA	PIPO W OR&WA	61.5	1.0	238	6
Pinus ponderosa, E OR&WA	Ponderosa pine, E OR&WA	PIPO E OR&WA	103.0	1.0	207	5
Pinus radiata	Monterey pine	PIRA	39.1	3.5	148	20
Pinus sabiniana	Gray pine	PISA	42.6	1.0	149	6
Pinus monophylla	Singleleaf pinyon	PIMO	76.1	1.0	140	1
Pinus washoensis	Washoe pine	PIWA	35.2	2.7	115	10
Pinus longaeva	Bristlecone pine	PILO	54.8	2.5	72	11
Pseudotsuga macrocarpa	Bigcone Douglas-fir	PSMA	62.2	5.6	148	20
Pseudotsuga menziesii, CA	Douglas-fir, CA	PSME - CA	93.7	1.0	237	6
Pseudotsuga menziesii, W OR&WA	Douglas-fir, W OR&WA	PSME W OR&WA	112.2	1.0	303	5
Pseudotsuga menziesii, W OR&WA	Douglas-fir, W OR&WA	PSME E OR&WA	90.0	1.0	228	5
Sequoia sempervirens	Redwood	SESE	157.6	1.0	309	7

Table 2 (continuation). Maximum and minimum values of diameter and height for specie

Specie	Common Name	Code SPP	DIA max	DIA min	h max	h min
Sequoiadendron giganteum	Giant sequoia	SEGI	150.9	1.0	283	6
Taxus brevifolia	Pacific yew	TABR	27.6	1.0	56	5
Thuja plicata	Western redcedar	THPL	139.5	1.0	256	5
Thuja plicata, NE WA	Western redcedar, NE WA	THPL NE WA	64.7	1.0	174	6
Torreya californica	California nutmeg	TOCA	31.4	1.0	94	7
Tsuga heterophyla	Western hemlock	TSHE	102.0	1.0	252	5
Tsuga heterophyla, NE WA	Western hemlock, NE WA	TSHE NE WA	39.8	1.0	156	6
Tsugamertensiana	Mountain hemlock	TSME	65.4	1.0	182	5
Acer macrophyllum	Bigleaf maple	ACMA	57.5	1.0	160	8
Acer negundo	Boxelder	ACNE	24.4	5.0	70	23
Aesculus californica	California buckeye	AECA	19.6	1.0	83	6
Alnus rubra	Red alder	ALRU	58.0	1.0	155	7
Alnus rhombifolia	White alder	ALRH	46.8	1.0	160	11
Arbutus menziesii	Pacific madrone	ARME	71.5	1.0	140	6
Betula spp	Water birch / Paper birch	Betula	14.4	1.0	87.5	12.5
Chrysolepis chrysophylla	Giant chinkapin	CHCH	41.5	1.0	124	6
Cornus nuttallii	Pacific dogwood	CONU	11.8	1.0	74	7
Fraxinus latifolia	Oregon ash	FRLA	39.6	1.0	110	7
Juglans hindsii / californica	California black walnut	JUGLA	31.2	5.3	80	15
Lithocarpus densiflorus	Tanoak	LIDE	88.3	1.0	142	6
Malus fusca	Oregon crab apple	MAFU	13.9	1.0	65	7
Platanus racemosa	California sycamore	PLRA	45.7	1.7	150	18
Populus tremuloides	Quaking aspen	POTR	29.8	1.0	122	5
Populus balsamifera trichocarpa	Black cottonwood	POBAT	62.2	1.0	197	9
Populus fremontii	Fremont’s cottonwood	POFR	38.4	1.5	156	12
Prosopis spp.	Mesquite	Prosopis	34.4	2.7	36	8
Prunus virginiana	Chokecherry	PRVI	12.3	1.0	87	7
Prunus emarginata	Bitter cherry	PREM	17.5	1.0	105	7
Quercus agrifolia	Coast live oak	QUAG	59.3	1.0	112	7
Quercus chrysolepis	Canyon live oak	QUCH	82.3	1.0	116	5
Quercus douglasii	Blue oak	QUDO	54.0	1.0	76	6
Quercus engelmannii	Engelmann oak	QUEN	35.9	5.9	57	29
Quercus garryana	Oregon white oak	QUGA	48.6	1.0	117	5

Table 2 (continuation). Maximum and minimum values of diameter and height for specie

Specie	Common Name	Code SPP	DIA max	DIA min	h max	h min
Quercus kelloggii	California black oak	QUKE	61.3	1.0	154	5
Quercus lobata	California white oak	QULO	50.8	1.2	102	7
Quercus wislizeni	Interior live oak	QUWI	41.6	1.0	98	5
Robinia pseudoacacia	Black locust	ROPS	33.7	5.8	104	41
Umbellularia californica	California-laurel	UMCA	56.3	1.0	130	5
Olneya tesota	Desert ironwood	OLTE	29.4	6.0	36	9

Note. The diameter is measured in inches and the height in feet. CA: California, OR: Oregon, WA: Washington, N: North, E: East, W: West, NE: Northeast

Some common species with wide distribution were divided into different regions, and some species with insufficient data were grouped with other similar species (Table 3).

Table 3. Species studied, number of plots and number of trees

Specie	Code SPP	Plots	Trees
Abies amabilis	ABAM	1742	24431
Abies concolor & grandis, CA	ABCO, CA	1832	22534
Abies concolor & grandis, W OR&WA	ABCO, W OR&A	979	6506
Abies concolor & grandis, E OR&WA	ABCO, E OR&A	2516	28059
Abies lasiocarpa	ABLA	1118	11064
Abies magnifica	ABMA	805	11372
Abies procera	ABPR	557	3396
Chamaecyparis lawsoniana	CHLA	124	808
Chamaecyparis nootkatensis	CHNO	209	1488
Cupressus spp.	Cupressus	9	100
Juniperus californica	JUCA	130	817
Juniperus occidentalis	JUOC	1438	8222
Juniperus osteosperma	JUOS	58	341
Larix lyallii	LALI	42	325
Larix occidentalis	LAOC	1564	7187
Calocedrus decurrens	CADE	2011	13676
Picea breweriana	PIBR	11	41
Picea engelmannii	PIEN	1059	6164
Picea sitchensis	PISI	376	1803
Pinus albicaulis, CA	PIAL CA	84	1121

Table 3 (continuation). Species studied, number of plots and number of trees

Specie	Code SPP	Plots	Trees
Pinus albicaulis, OR&WA	PIAL OR&WA	195	952
Pinus attenuata	PIAT	122	595
Pinus balfouriana	PIBA	23	349
Pinus contorta, CA	PICO CA	479	6813
Pinus contorta, OR&WA	PICO OR&WA	2584	35905
Pinus contorta var. contorta	PICO Coast	52	641
Pinus coulteri	PICOUL	46	137
Pinus flexilis	PIFL	27	147
Pinus jeffreyi	PIJE	1237	10878
Pinus lambertiana	PILA	1583	5227
Pinus monticola	PIMO	840	2736
Pinus muricata	PIMU	9	117
Pinus ponderosa, CA	PIPO CA	1680	14769
Pinus ponderosa, W OR&WA	PIPOW OR&WA	370	1766
Pinus ponderosa, E OR&WA	PIPO E OR&WA	4633	45505
Pinus radiata	PIRA	6	45
Pinus sabiniana	PISA	298	779
Pinus monophylla	PIMO	385	3478
Pinus washoensis	PIWA	5	53
Pinus longaeva	PILO	8	139
Pseudotsuga macrocarpa	PSMA	68	252
Pseudotsuga menziesii, CA	PSME - CA	1327	15564
Pseudotsuga menziesii, W OR&WA	PSME W OR&WA	6446	106860
Pseudotsuga menziesii, W OR&WA	PSME E OR&WA	3962	36031
Sequoia sempervirens	SESE	303	6495
Sequoiadendron giganteum	SEGI	39	279
Taxus brevifolia	TABR	357	879
Thuja plicata	THPL	1836	10780
Thuja plicata, NE WA	THPL NE WA	304	4030
Torreya californica	TOCA	32	106
Tsuga heterophyla	TSHE	3839	45100
Tsuga heterophyla, NE WA	TSHE NE WA	147	1398
Tsugamertensiana	TSME	1053	12903
Acer macrophyllum	ACMA	1328	5843

Table 3 (continuation). Species studied, number of plots and number of trees

Specie	Code SPP	Plots	Trees
Acer negundo	ACNE	7	26
Aesculus californica	AECA	127	671
Alnus rubra	ALRU	1910	13254
Alnus rhombifolia	ALRH	105	402
Arbutus menziesii	ARME	1215	6812
Betula spp	Betula	138	633
Chrysolepis chrysophylla	CHCH	514	2275
Cornus nuttallii	CONU	252	629
Fraxinus latifolia	FRLA	95	406
Juglans hindsii / californica	JUGLA	4	26
Lithocarpus densiflorus	LIDE	923	15601
Malus fusca	MAFU	41	105
Platanus racemosa	PLRA	28	67
Populus tremuloides	POTR	191	1078
Populus balsamifera trichocarpa	POBAT	243	771
Populus fremontii	POFR	11	51
Prosopis spp.	Prosopis	7	60
Prunus virginiana	PRVI	51	157
Prunus emarginata	PREM	298	837
Quercus agrifolia	QUAG	343	2480
Quercus chrysolepis	QUCH	1418	16254
Quercus douglasii	QUDO	514	3976
Quercus engelmannii	QUEN	6	22
Quercus garryana	QUGA	488	4612
Quercus kelloggii	QUKE	1403	8337
Quercus lobata	QULO	97	346
Quercus wislizeni	QUWI	385	3601
Robinia pseudoacacia	ROPS	3	21
Umbellularia californica	UMCA	443	3017
Olneya tesota	OLTE	8	20

Note. CA: California, OR: Oregon, WA: Washington, N: North, E: East, W: West, NE: Northeast

4.4 STATISTICS MODELS

A mixed model is a statistical model containing both fixed effects and random effects. These models are particularly useful in settings where measurements are made on clusters of related statistical units (Fiztmaurice et al 2004).

We use these mixed models because improves the accuracy and precision of height prediction over the conventional nonlinear fixed models that assumes the observations are independent. When two or more heights were randomly subsampled, then the mixed models efficiently explained the differences in the height-diameter relationship because of the variations in relative position of trees and stand density without having to incorporate them into the model (Temesgen et al, 2008).

We can calibrate the model to the plot using the subsample of trees that are measured. This increases the accuracy of the prediction and improves the results by applying volume models. We can have two situations: (1) we do not have measurements of the species of interest in the plot, in this case we cannot calibrate, so we have to use HT-DIA models and assume the independent errors. (2) We have measurements of the species of interest, so we can calculate the setting and applying the mix models.

We choose the Chapman-Richards equation to relate height and diameter in this study. (Garman et al., 1995) fitted the following Chapman-Richards model to a data set from western Oregon, believing that this model form best accounted for the expected asymptotic behavior in the height-diameter relationship (Hanus et al, 1999):

$$HT = 4.5 + a_0 * (1 – \exp (b_1 * DIA))^{b2}$$

- a_0: asymptotic height
- b_1: steepness parameter
- b_2: curvature parameter

The generalized Chapman-Richards model was derived from the Chapman-Richards function in which parameters a_0, b_1, b_2 were unconstrained. This model is suitable in forestry to represent some typical growth patterns of trees and stands. The generalized Chapman-Richards model was capable of describing a wide range of growth curves that was asymptotic or non-asymptotic, with or without inflection point. The model has been widely applied in forestry thanks to its flexibility, accuracy, and meaningful analytical properties (Zhao-Gang and Feng-Ri, 2003).

Also, we used an internal validation techniques, the leave-one-plot-out cross validation. One plot was excluded from the dataset, then, the model is fitted with the remaining observations, and used to predict the observations from the excluded plot. The process is repeated over all of the plots in the dataset. Because the model was fitted without the observation that was later predicted, the prediction is not biased by that observation and we can assess how well the model will behave when predicting a new observation (Monleon et al, 2004).

The rationale behind this method is that observations from the same plot tend to be correlated. Excluding a plot from the dataset to examine the performance of the models provides stronger model evaluation for a new plot that was not included in the original dataset (Monleon et al, 2004).

Once the predicted values were calculated, for each species, we calculate the following estimates:

- Bias (same units than heights, feet):

$$BIAS = (1/n)\sum_{i=1}^{n}(\hat{h}_i - h_i)$$

Where *n* is the number of estimations of the specie, $\hat{h}_i$, is predicted height of the *i* tree with the cross validation, and h_i is height tree.

- Relative bias (%):

$$RBIAS = (1/n)\sum_{i=1}^{n}\frac{(\hat{h}_i - h_i)}{h_i}$$

- Root mean square error (same units than heights, feet):

$$RMSE = (1/n)\sum_{i=1}^{n}(\hat{h}_i - h_i)^2$$

- Relative root mean square error (%):

$$RRMSE = (1/n)\sum_{i=1}^{n}\left[\frac{(\hat{h}_i - h_i)}{h_i}\right]^2$$

- Estimate of the coefficient of determination:

$$CD = cor\left(\hat{h}_i, h_i\right)^2$$

Where *cor* is correlation.

We have performed all the statistics using R 3.1.1 (2014) program (see Appendix I, Statistics Models with R).

5. RESULTS AND DISCUSSION

5.1 CHAPMAN-RICHARDS MODEL

We applied the following Chapman-Richards model to all species:

$$HT = 4.5 + a_0 * (1 - \exp(b_1 * DIA))^{b2}$$

- a_0: asymptotic height
- b_1: steepness parameter
- b_2: curvature parameter

Table 4 contains the regression coefficients and mean square errors (MSE) for all species. For *Cupressus* spp. (CUPRE), *Juniperus californica* (JUCA), *Juniperus osteosperma* (JUOS), *Picea breweriana* (PIBR), *Pinus radiata* (PIRA), *Pinus sabiniana* (PISA), *Pseudotsuga macrocarpa* (PSMA), *Acer Negundo* (ACNE), *Aesculus californica* (AECA), *Cornus nuttallii* (CONU4), *Malus fusca* (MAFU), *Platanus racemosa* (PLRA), *Prosopis* spp. (PROSO), *Prunus virginiana* (PRVI), *Quercus douglasii* (QUDO), *Quercus engelmannii* (QUEN), *Quercus wislizeni* (QUWI2), *Robinia pseudoacacia* (ROPS), and *Umbellularia californica* (UMCA) we had not enough observations, or the Chapman-Richards model did not fit so the values are 0.

Hanus et al. (1999) used the same equation for Douglas fir (PSME) in Western Washington and Northwestern Oregon, west of the Cascades, and obtain this values, a_0=167.68, b_1=-0.07, b_2=1.3. The coefficient for the asymptotic height is low than our value, probably due to the young age of the trees in the modeling data set (Hanus et al., 1999). The values of the MSE are similar to the Hanus' results.

Garman et al. (1995) used a Chapman-Richards equation too, in twenty-four species. Their equations were only for species in Western Oregon but they obtained similar results. For example, we have obtained 172.058 in a_0 parameter, in Pacific silver fir (ABAM), and Garman et al. (1995) obtained 196 approx. In Red fir (ABMA) we have obtained 166.022 and they obtained 196. In Western redcedar (THPL) we have obtained 174.308 and Garman et al. (1995) obtained 177. In Red alder (ALRU) we have obtained 102.340 and they 114.

Overall, the high values of the adjust coefficient of determination indicate the adequacy of the Chapman-Richards function to predict height from diameter (Garman et al. 1995).

Table 2. Regression coefficients and mean square errors for Chapman-Richards model

Specie	SPP	a_0	b_1	b_2	MSE
Abies amabilis	ABAM	172.058	-0.054	1.361	12.468
Abies concolor & grandis, CA	ABCO, CA	183.688	-0.034	1.164	14.654
Abies concolor & grandis, W OR&WA	ABCO, W OR&A	174.900	-0.046	1.179	16.374
Abies concolor & grandis, E OR&WA	ABCO, E OR&A	145.575	-0.051	1.182	12.682
Abies lasiocarpa	ABLA	96.262	-0.105	1.543	11.901
Abies magnifica	ABMA	166.022	-0.039	1.290	15.928
Abies procera	ABPR	210.856	-0.034	1.163	13.827
Chamaecyparis lawsoniana	CHLA	180.286	-0.028	0.966	15.355
Chamaecyparis nootkatensis	CHNO	131.305	-0.049	1.166	12.502
Cupressus spp.	Cupressus	0.000	0.000	0.000	0.000
Juniperus californica	JUCA	0.000	0.000	0.000	0.000
Juniperus occidentalis	JUOC	41.241	-0.081	0.870	8.053
Juniperus osteosperma	JUOS	0.000	0.000	0.000	0.000
Larix lyallii	LALI	79.589	-0.091	1.210	8.506
Larix occidentalis	LAOC	131.194	-0.090	1.150	13.946
Calocedrus decurrens	CADE	177.158	-0.025	1.096	12.326
Picea breweriana	PIBR	0.000	0.000	0.000	0.000
Picea engelmannii	PIEN	143.633	-0.066	1.284	13.906
Picea sitchensis	PISI	230.009	-0.024	0.949	21.990
Pinus albicaulis, CA	PIAL CA	54.321	-0.068	1.203	6.467
Pinus albicaulis, OR&WA	PIAL OR&WA	48.022	-0.126	1.284	8.769
Pinus attenuata	PIAT	119.725	-0.062	1.124	12.350
Pinus balfouriana	PIBA	60.810	-0.046	0.927	12.729
Pinus contorta, CA	PICO CA	83.898	-0.092	1.429	15.343
Pinus contorta, OR&WA	PICO OR&WA	82.546	-0.150	1.562	11.825
Pinus contorta var. contorta	PICO Coast	156.405	-0.026	0.860	12.339
Pinus coulteri	PICOUL	119.139	-0.041	1.151	13.496
Pinus flexilis	PIFL	70.024	-0.028	0.757	12.448
Pinus jeffreyi	PIJE	161.839	-0.029	1.140	14.055
Pinus lambertiana	PILA	247.665	-0.019	0.995	18.053
Pinus monticola	PIMO	105.458	-0.075	1.318	18.507

Table 3 (continuation). Regression coefficients and mean square errors for Chapman-Richards model

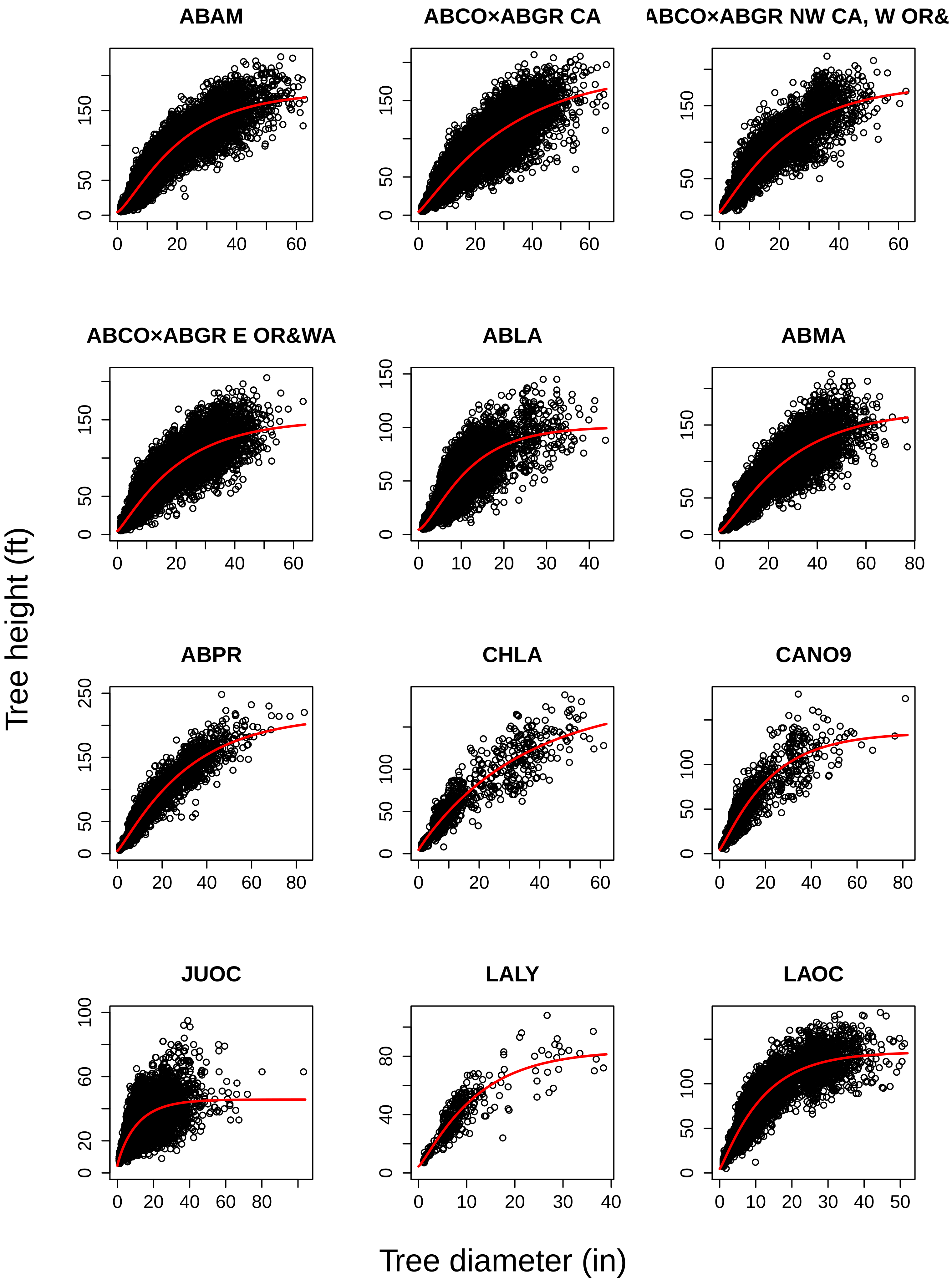
Specie	Code SPP	a_0	b_1	b_2	MSE
Pinus muricata	PIMU	218.635	-0.022	0.918	16.065
Pinus ponderosa, CA	PIPO CA	221.543	-0.028	1.185	14.597
Pinus ponderosa, W OR&WA	PIPO W OR&WA	253.139	-0.024	1.148	13.862
Pinus ponderosa, E OR&WA	PIPO E OR&WA	159.034	-0.040	1.193	12.242
Pinus radiata	PIRA	0.000	0.000	0.000	0.000
Pinus sabiniana	PISA	0.000	0.000	0.000	0.000
Pinus monophylla	PIMO	26.923	-0.183	2.549	7.307
Pinus washoensis	PIWA	98.158	-0.104	2.153	14.788
Pinus longaeva	PILO	38.957	-0.116	1.344	10.998
Pseudotsuga macrocarpa	PSMA	0.000	0.000	0.000	0.000
Pseudotsuga menziesii, CA	PSME - CA	200.855	-0.030	0.962	16.452
Pseudotsuga menziesii, W OR&WA	PSME W OR&WA	213.619	-0.037	1.059	19.089
Pseudotsuga menziesii, W OR&WA	PSME E OR&WA	137.154	-0.052	1.047	14.312
Sequoia sempervirens	SESE	257.105	-0.018	0.890	19.458
Sequoiadendron giganteum	SEGI	243.989	-0.027	1.265	19.191
Taxus brevifolia	TABR	59.240	-0.046	0.832	5.811
Thuja plicata	THPL	174.308	-0.032	0.984	15.039
Thuja plicata, NE WA	THPL NE WA	127.081	-0.064	1.126	9.282
Torreya californica	TOCA	89.157	-0.066	1.094	6.884
Tsuga heterophyla	TSHE	177.286	-0.049	1.135	15.040
Tsuga heterophyla, NE WA	TSHE NE WA	117.668	-0.112	1.468	10.874
Tsugamertensiana	TSME	117.420	-0.070	1.519	12.288
Acer macrophyllum	ACMA3	96.498	-0.090	0.941	14.739
Acer negundo	ACNE	0.000	0.000	0.000	0.000
Aesculus californica	AECA	28.871	-0.125	0.703	0.000
Alnus rubra	ALRU	102.340	-0.100	1.029	13.773
Alnus rhombifolia	ALRH	88.502	-0.087	1.081	11.835
Arbutus menziesii	ARME	82.229	-0.066	0.901	11.156
Betula spp	Betula	89.442	-0.113	0.910	
Chrysolepis chrysophylla	CHCH	0.000	0.000	0.000	0.000

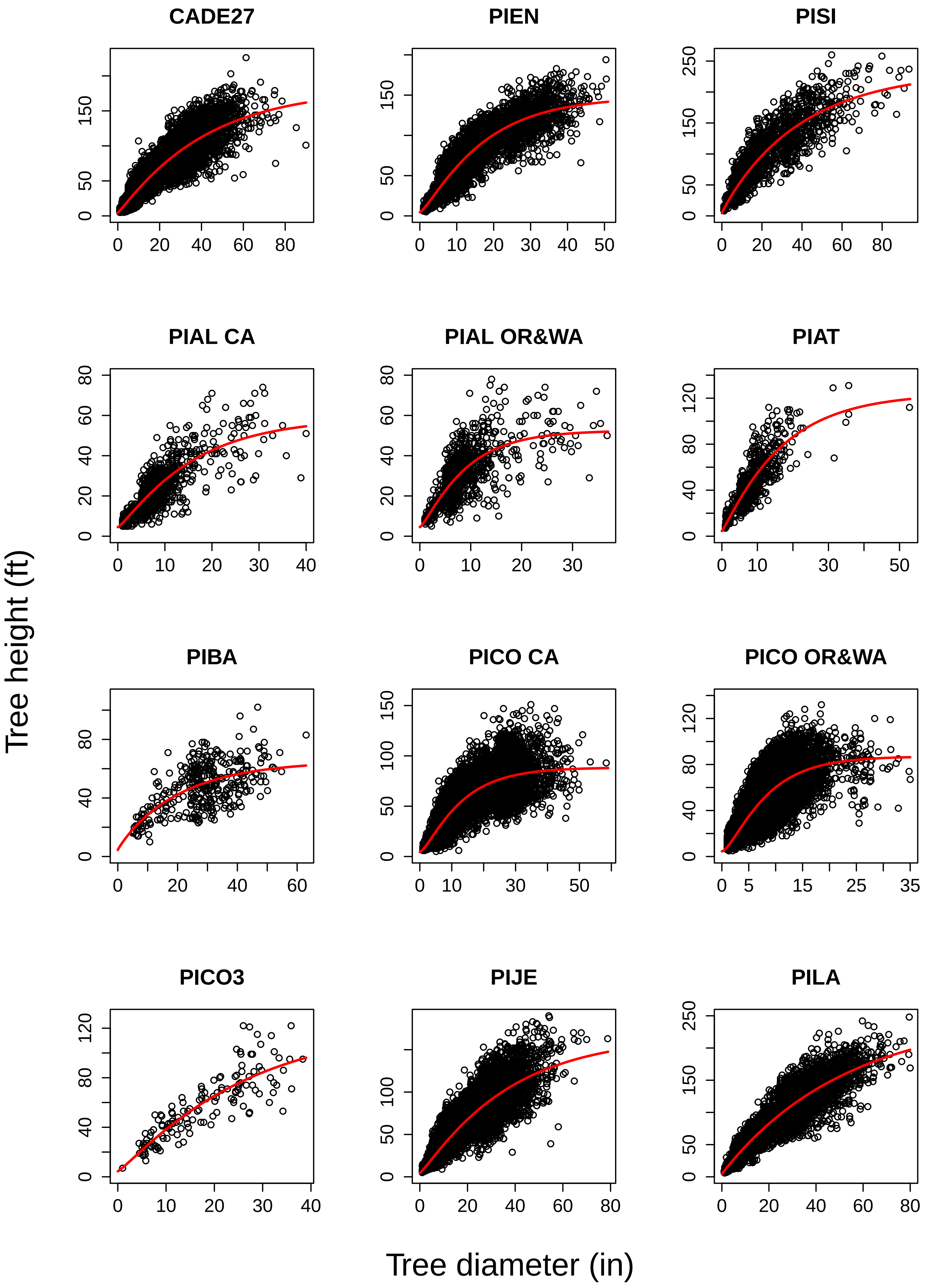
Table 4 (continuation). Regression coefficients and mean square errors for Chapman-Richards model

Specie	Code SPP	a_0	b_1	b_2	MSE
Cornus nuttallii	CONU	41.449	-0.251	1.072	0.000
Fraxinus latifolia	FRLA	88.246	-0.088	0.840	13.192
Juglans hindsii / californica	JUGLA	64.492	-0.335	7.092	9.931
Lithocarpus densiflorus	LIDE	103.200	-0.061	0.934	10.924
Malus fusca	MAFU	0.000	0.000	0.000	0.000
Platanus racemosa	PLRA	0.000	0.000	0.000	0.000
Populus tremuloides	POTR	99.463	-0.099	1.416	13.765
Populus balsamifera trichocarpa	POBAT	157.273	-0.041	0.813	20.900
Populus fremontii	POFR	115.279	-0.101	2.110	16.672
Prosopis spp.	Prosopis	0.000	0.000	0.000	0.000
Prunus virginiana	PRVI	0.000	0.000	0.000	0.000
Prunus emarginata	PREM	82.913	-0.142	1.099	10.511
Quercus agrifolia	QUAG	58.681	-0.051	0.813	9.489
Quercus chrysolepis	QUCH	75.459	-0.049	0.944	8.499
Quercus douglasii	QUDO	0.000	0.000	0.000	0.000
Quercus engelmannii	QUEN	0.000	0.000	0.000	0.000
Quercus garryana	QUGA	58.387	-0.102	1.232	9.879
Quercus kelloggii	QUKE	84.724	-0.046	0.784	11.775
Quercus lobata	QULO	60.691	-0.126	1.583	13.344
Quercus wislizeni	QUWI	0.000	0.000	0.000	0.000
Robinia pseudoacacia	ROPS	0.000	0.000	0.000	0.000
Umbellularia californica	UMCA	0.000	0.000	0.000	0.000
Olneya tesota	OLTE	22.462	-0.123	2.431	5.973

Note; a_0: asymptotic height, b_1:steepness parameter, b_2: curvature parameter

Below, the height-diameter plots for the species fitted with Chapman-Richards model are shown.


ABAM
ABCO×ABGR CA
ABCO×ABGR NW CA, W OR&
ABCO×ABGR E OR&WA
ABLA
ABMA
ABPR
CHLA
CANO9
JUOC
LALY
LAOC
0
50
100
150
250
20
40
60
80
0
10
20
30
40
50
Tree height (ft)
Tree diameter (in)


CADE27
PIEN
PISI
PIAL CA
PIAL OR&WA
PIAT
PIBA
PICO CA
PICO OR&WA
PICO3
PIJE
PILA
Tree height (ft)
Tree diameter (in)
0
50
150
0
20
40
60
80
0
50
150
0
10
20
30
40
50
0
50
150
250
0
20
40
60
80
0
20
40
60
80
0
10
20
30
40
0
20
40
60
80
0
10
20
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40
80
120
0
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30
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0
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80
0
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0
50
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150
0
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30
50
0
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0
40
80
120
0
10
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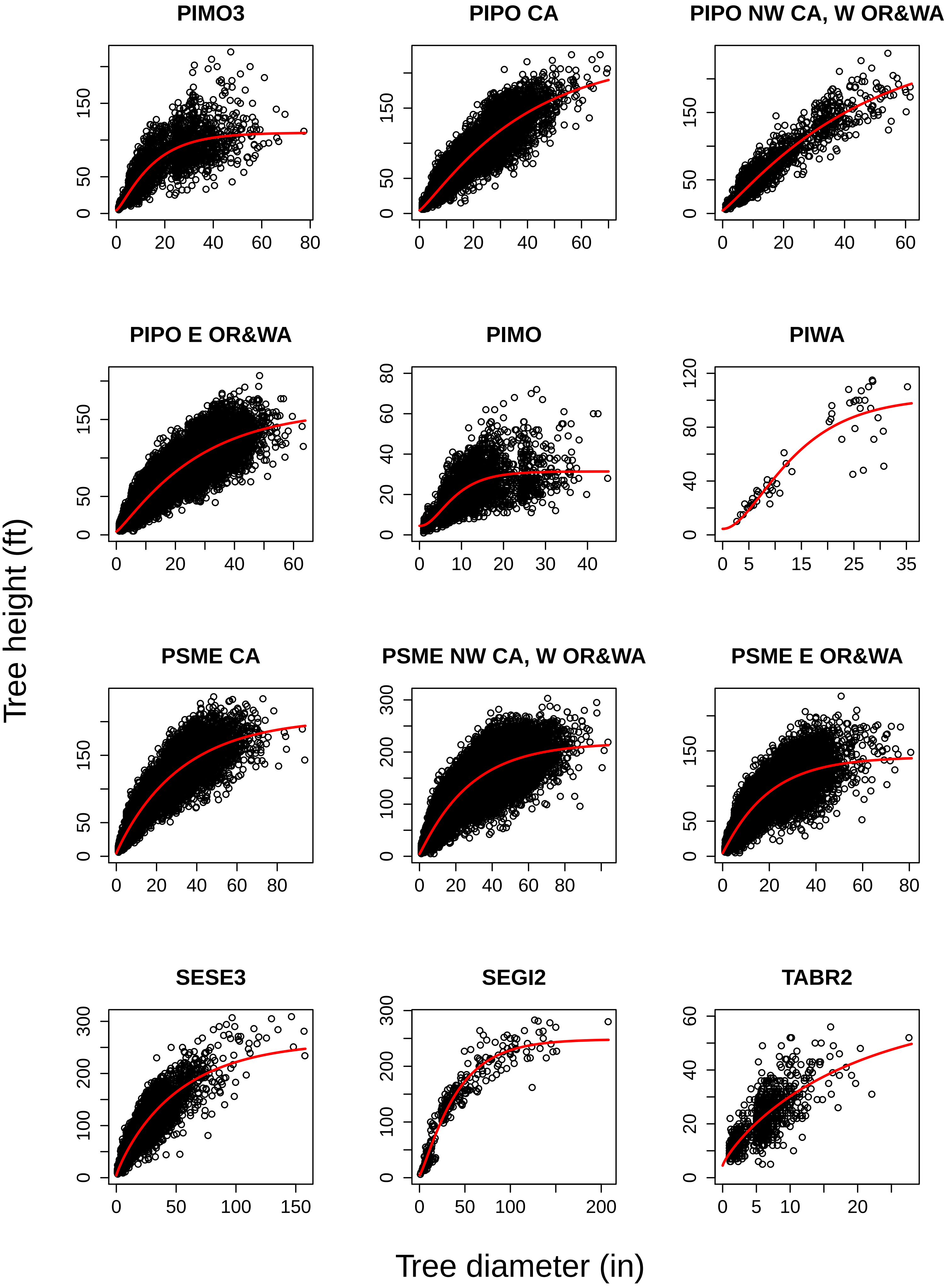
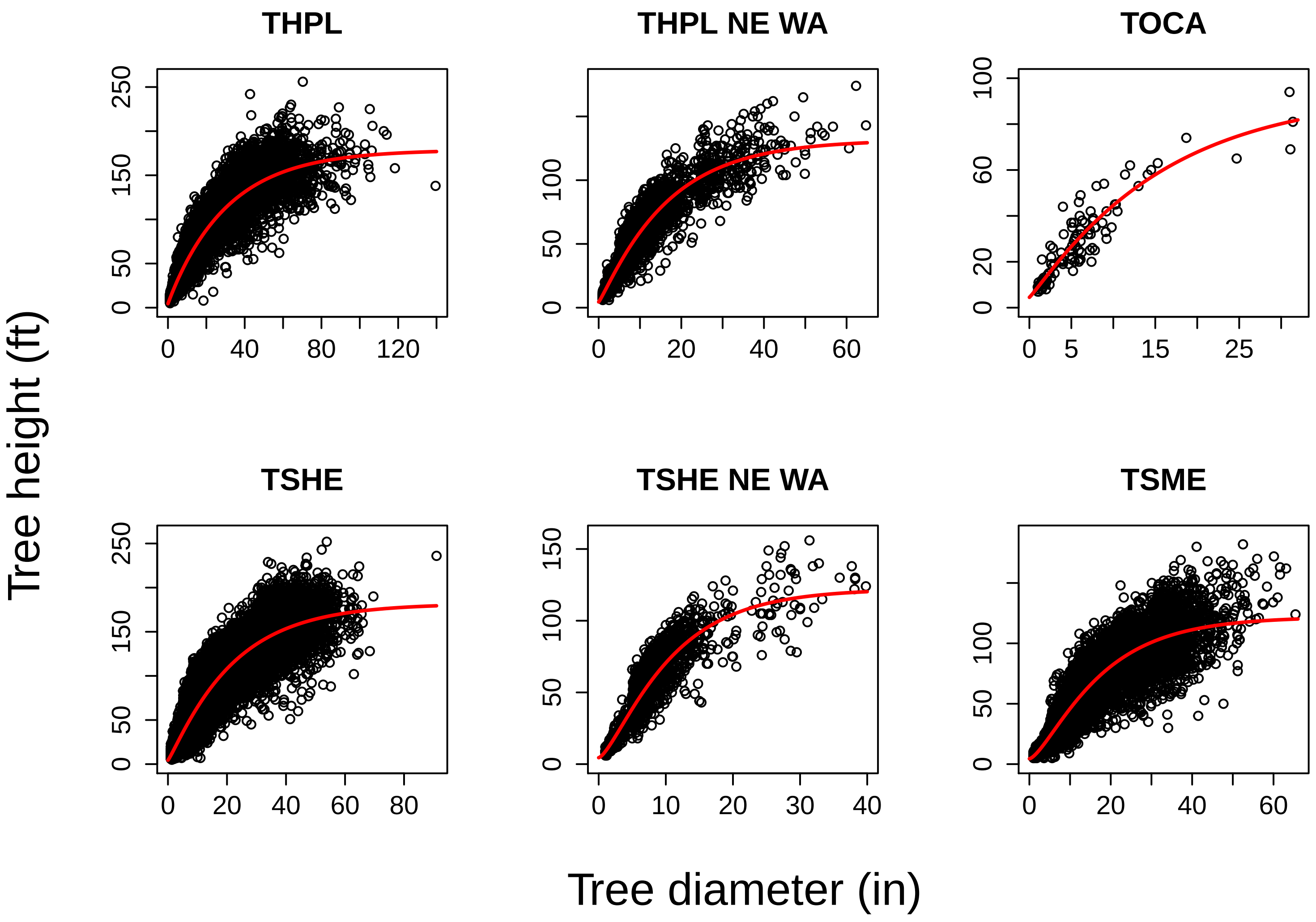
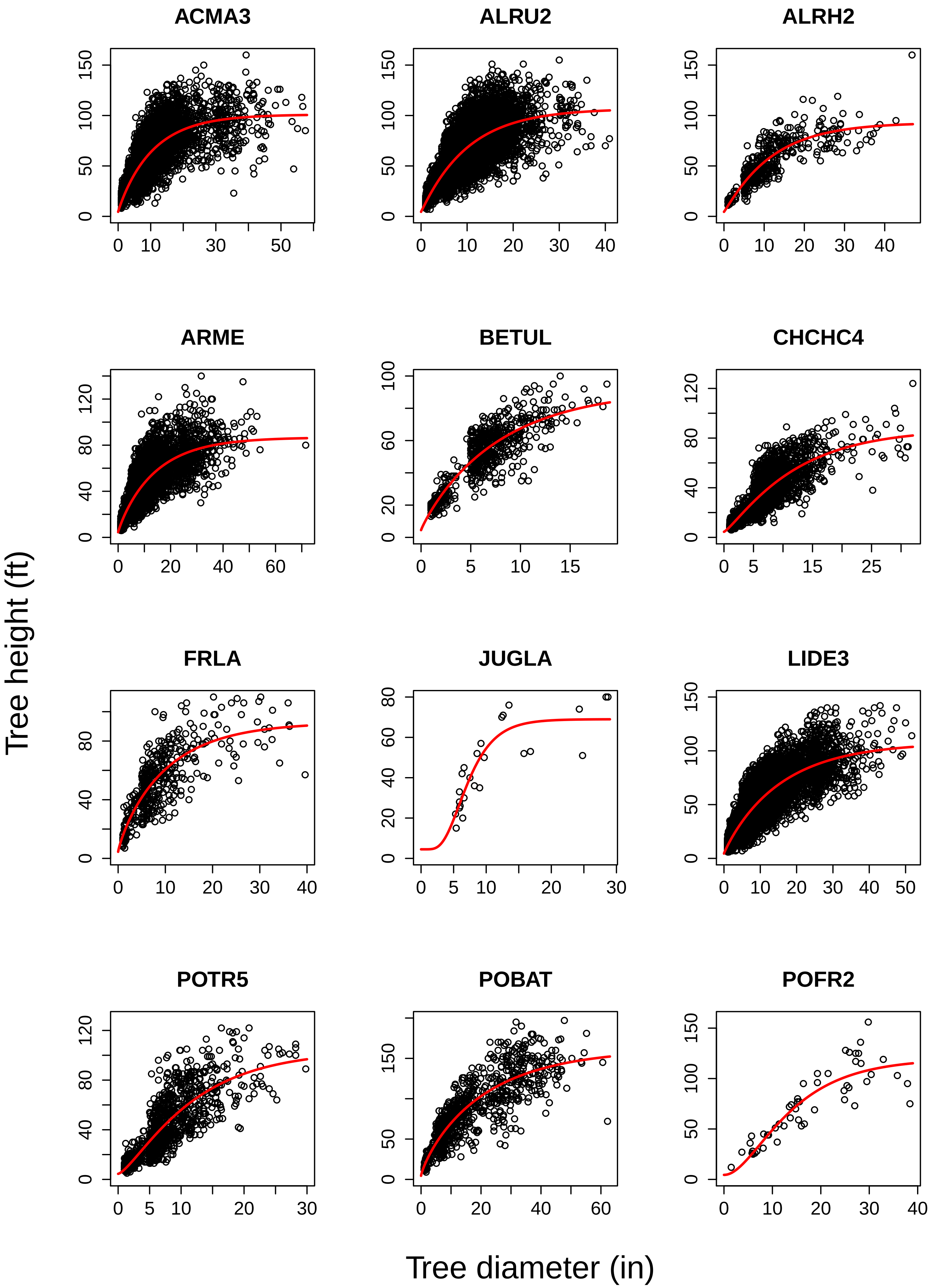
20
40
60
80
50
150
250
0
20
40
60
80


PIMO3
PIPO CA
PIPO NW CA, W OR&WA
PIPO E OR&WA
PIMO
PIWA
PSME CA
PSME NW CA, W OR&WA
PSME E OR&WA
SESE3
SEGI2
TABR2
Tree height (ft)
Tree diameter (in)
0
50
100
150
200
300
0
20
40
60
80
120
0
5
10
15
20
25
30
35
40
50
60
80
100
150
200


THPL
THPL NE WA
TOCA
TSHE
TSHE NE WA
TSME
Tree height (ft)
Tree diameter (in)
0
50
150
250
0
40
80
120
0
50
100
0
20
40
60
0
20
60
100
0
5
15
25
0
50
150
250
0
20
40
60
80
0
50
100
150
0
10
20
30
40
0
50
100
0
20
40
60


ACMA3
ALRU2
ALRH2
ARME
BETUL
CHCHC4
FRLA
JUGLA
LIDE3
POTR5
POBAT
POFR2
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50
100
150
0
40
80
120
0
20
60
100
0
10
30
50
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10
20
30
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20
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60
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5
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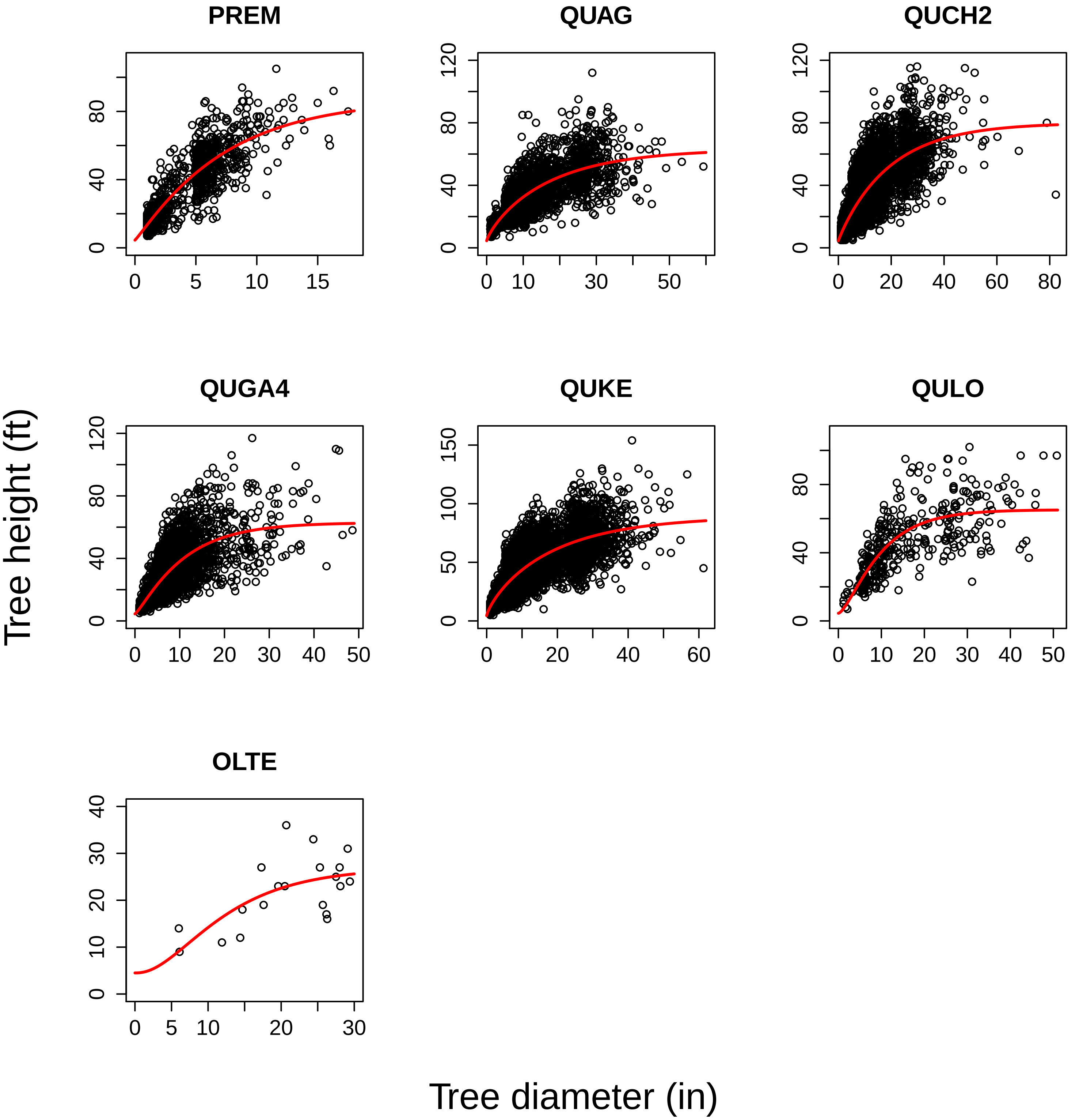
5
15
25
0
10
20
30
40
0
5
10
20
30
50
0
10
20
30
40
50
0
20
40
60
Tree height (ft)
Tree diameter (in)


PREM
QUAG
QUCH2
QUGA4
QUKE
QULO
OLTE
Tree height (ft)
Tree diameter (in)
0
40
80
120
150
100
50
0
10
20
30
40
5
10
15
20
30
50
40
60
80

5.2 LEAVE-ONE-PLOT-OUT CROSS VALIDATION

We calculate the following estimates:

- Bias (feet):

$$BIAS = (1/n)\sum_{i=1}^{n}(\hat{h}_i - h_i)$$

Where *n* is the number of estimations of the specie, $\hat{h}_i$, is predicted height of the *i* tree with the cross validation, and h_i is height tree.

- Relative bias (%):

$$RBIAS = (1/n)\sum_{i=1}^{n}\frac{(\hat{h}_i - h_i)}{h_i}$$

- Root mean square error (feet):

$$RMSE = (1/n)\sum_{i=1}^{n}(\hat{h}_i - h_i)^2$$

- Relative root mean square error (%):

$$RRMSE = (1/n)\sum_{i=1}^{n}\left[\frac{(\hat{h}_i - h_i)}{h_i}\right]^2$$

- Estimate of the coefficient of determination:

$$CD = cor(\hat{h}_i, h_i)^2$$

Where *cor* is correlation.

Table 5 shows the results of the leave-one-plot-out cross validation. BIAS is an estimate of the bias ratio and provides a check of the unbiasedness of the prediction. It should be approximately 0 (Monleon et al. 2004). In general, our results are too close by 0, except *Pinus washoensis* (PIWA), with BIAS=-9.33, *Pinus longaeva* (PILO), with BIAS=-3.46, and *Juglans hindsii/californica* (JUGLA), with BIAS=-5.35, these results are higher than desired. This suggests that the predictions are virtually unbiased. The BIAS factor is the ratio of the bias to an estimate of the mean squared prediction error (Monleon et al. 2004).

Smaller values of RMSE indicate that the predicted values are close to the actual values (Monleon et al. 2004). In our case the values are higher than the values obtained by Temesgen et al. (2006) in species of Southwest Oregon.

The coefficient of determination, CD would provide a measure of the fit of the model in nonlinear regression, equivalent to R^2, and has a very direct interpretation (Monleon et al, 2004). A good value of this coefficient is close by 1, and, except *Olneya tesota* (OLTE) which value is 0.19, our CD results, in general, are quite close to 1.

The leave-one-plot-out cross validation method should be a more accurate measure of the predictive performance of the models for new observations because the observation used to fit the model are always from a different plot (Monleon et al, 2004).

We had a problem with some species, the model did not converge when a plot was deleted. Most species were problematic because the model was not appropriated. These species were *Pinus contorta* var. *contorta* (PICO Coast), *Pinus flexilis* (PIFL), *Pinus muricata* (PIMU), and *Pinus longaeva* (PILO).

Table 5. Leave-one-plot-out cross validation parameters

Specie	Code SPP	BIAS	RBIAS	RMSE	RRMSE	CD
Abies amabilis	ABAM	0.16	7.56	12.49	28.52	0.89
Abies concolor & grandis, CA	ABCO, CA	0.04	5.97	14.67	26.95	0.86
Abies concolor & grandis, W OR&WA	ABCO, W OR&A	0.10	7.85	16.43	32.28	0.84
Abies concolor & grandis, E OR&WA	ABCO, E OR&A	0.06	6.35	12.69	27.27	0.86
Abies lasiocarpa	ABLA	0.06	9.06	11.92	35.63	0.73
Abies magnifica	ABMA	0.07	6.45	15.97	27.24	0.86
Abies procera	ABPR	0.20	7.07	13.90	26.09	0.91
Chamaecyparis lawsoniana	CHLA	0.16	8.40	15.66	33.14	0.85
Chamaecyparis nootkatensis	CHNO	0.11	7.31	12.70	28.21	0.84
Juniperus occidentalis	JUOC	0.01	7.46	8.06	31.73	0.49
Larix lyallii	LALI	-0.02	4.63	8.82	24.21	0.77

Table 6 (continuation). Leave-one-plot-out cross validation parameters

Specie	Code SPP	BIAS	RBIAS	RMSE	RRMSE	CD
Larix occidentalis	LAOC	0.03	4.45	13.98	23.59	0.81
Calocedrus decurrens	CADE	0.01	5.43	12.34	25.86	0.87
Picea engelmannii	PIEN	0.08	6.76	13.94	29.06	0.86
Picea sitchensis	PISI	-0.04	8.23	22.35	32.40	0.82
Pinus albicaulis, CA	PIAL CA	-0.02	8.22	6.56	37.45	0.65
Pinus albicaulis, OR&WA	PIAL OR&WA	0.02	9.82	8.85	40.55	0.57
Pinus attenuata	PIAT	-0.16	6.31	12.73	30.32	0.67
Pinus balfouriana	PIBA	-0.12	8.92	13.61	36.45	0.31
Pinus contorta, CA	PICO CA	-0.02	9.68	15.41	39.98	0.67
Pinus contorta, OR&WA	PICO OR&WA	-0.06	7.54	11.84	34.10	0.67
Pinus contorta var. contorta	PICO	0.00	5.42	14.02	26.83	0.71
Pinus jeffreyi	PIJE	0.03	7.01	14.08	29.52	0.81
Pinus lambertiana	PILA	0.08	5.69	18.08	25.44	0.85
Pinus monticola	PIMO	0.08	9.60	18.58	37.17	0.73
Pinus ponderosa, CA	PIPO CA	-0.04	5.85	14.62	27.85	0.86
Pinus ponderosa, W OR&WA	PIPO W OR&WA	-0.04	5.96	13.96	27.25	0.89
Pinus ponderosa, E OR&WA	PIPO E OR&WA	-0.03	4.86	12.25	25.21	0.87
Pinus sabiniana	PISA	0.01	4.83	11.48	24.19	0.78
Pinus monophylla	PIMO	0.02	13.67	7.34	46.28	0.46
Pinus washoensis	PIWA	-9.33	-13.48	25.66	43.14	0.51
Pinus longaeva	PILO	-3.46	-0.26	12.37	36.12	0.25
Pseudotsuga menziesii, CA	PSME - CA	0.01	4.59	16.48	23.07	0.87
Pseudotsuga menziesii, W OR&WA	PSME W OR&WA	0.01	4.99	19.10	25.25	0.86
Pseudotsuga menziesii, W OR&WA	PSME E OR&WA	0.05	5.71	14.32	27.38	0.81
Sequoia sempervirens	SESE	0.10	6.16	19.58	28.15	0.84
Sequoiadendron giganteum	SEGI	0.11	7.99	20.13	30.95	0.93

Table 7 (continuation). Leave-one-plot-out cross validation parameters

Specie	Code SPP	BIAS	RBIAS	RMSE	RRMSE	CD
Taxus brevifolia	TABR	-0.01	7.80	5.84	36.79	0.60
Thuja plicata	THPL	0.04	5.35	15.07	26.56	0.89
Thuja plicata, NE WA	THPL NE WA	0.09	5.75	9.42	23.04	0.89
Torreya californica	TOCA	0.06	6.58	7.41	26.85	0.82
Tsuga heterophyla	TSHE	0.04	6.68	15.05	29.93	0.85
Tsuga heterophyla, NE WA	TSHE NE WA	-0.01	5.10	11.03	23.66	0.84
Tsuga mertensiana	TSME	0.04	5.62	12.32	28.44	0.85
Acer macrophyllum	ACMA	-0.06	6.73	14.76	32.46	0.60
Aesculus californica	AECA	0.02	5.95	5.13	27.69	0.48
Alnus rubra	ALRU	-0.02	5.14	13.79	26.37	0.60
Alnus rhombifolia	ALRH	-0.01	4.13	12.16	24.79	0.72
Arbutus menziesii	ARME	0.02	6.87	11.17	29.23	0.62
Betula spp	Betula	-0.04	4.01	9.51	22.84	0.75
Chrysolepis chrysophylla	CHCH	-0.04	6.42	9.61	30.43	0.72
Cornus nuttallii	CONU	-0.01	5.91	6.28	29.24	0.66
Fraxinus latifolia	FRLA	-0.02	7.82	13.43	33.47	0.63
Juglans hindsii / californica	JUGLA	-5.35	-0.17	14.42	35.11	0.60
Lithocarpus densiflorus	LIDE	0.00	6.48	10.94	29.71	0.73
Populus tremuloides	POTR	-0.19	8.32	13.97	38.90	0.70
Populus balsamifera trichocarpa	POBAT	0.04	7.36	21.24	33.50	0.71
Populus fremontii	POFR	-0.05	3.70	21.06	29.22	0.64
Quercus agrifolia	QUAG	-0.01	7.09	9.54	31.71	0.55
Quercus chrysolepis	QUCH	-0.02	8.00	8.51	33.87	0.62
Quercus douglasii	QUDO	0.00	5.20	6.73	24.97	0.48
Quercus garryana	QUGA	-0.01	9.41	9.94	35.90	0.47
Quercus kelloggii	QUKE	0.03	8.37	11.79	33.53	0.60
Quercus lobata	QULO	0.02	8.48	13.77	35.44	0.51
Quercus wislizeni	QUWI	0.04	8.59	7.42	33.20	0.62
Umbellularia californica	UMCA	0.00	7.12	10.89	29.62	0.65
Olneya tesota	OLTE	-0.21	6.80	6.87	37.59	0.19

6. CONCLUSIONS

1. It is not necessary measure all trees' height in a plot because is possible to estimate this with height-diameter equations, knowing diameters and a sample of heights.

2. Use mixed models improves the accuracy and precision of height prediction over the conventional nonlinear fixed models that assumes the observations are independent.

3. Chapman-Richard model is suitable in forestry to represent some typical growth patterns of trees and stands and is capable of describing a wide range of growth curves.

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APPENDIX

APPENDIX I. STATISTICS MODELS WITH R

We used the followings R programs to develop this study.

First, we check how many trees there was in each species, made a plot only with this specie and identify the strange points and values to analyze.

```
check<-tree[tree$SPCD==202,]

plot(check$DIA,check$HT,main='ABAM')

identify(check$DIA,check$HT,atpen=T)

check[22388,]
```

Secondly we made a list with the number of trees by species and plots to split or group the species for the equations.

```
out1<-aggregate(tree$DIA,by=list(SPCD=tree$SPCD),length)

out2<-
aggregate(tree$DIA,by=list(PLOTID=tree$PLOTID,SPCD=tree$SPCD),length)

dim(out2)

out2[1:100,]

out3<-aggregate(out2$x,by=list(SPCD=out2$SPCD),length)

                  names(out3)<-c('SPCD','NUMPLOT')

                  names(out1)<-c('SPCD','NUMTREE')

sumtree<-merge(out3,out1)
```

Then, we applied the mixed model with Chapman-Richards equation.

```
namespp<-read.csv('spplistcode.csv')

spp<-sort(unique(tree$spcdnew))

numspp<-length(spp)


plotfit<-function(sppcode,name,coline,colpoint,a00,b10,b20) {

   nlfit<-nls(HT~4.5+a0*((1-exp(b1*DIA))^b2),data=tree,
   subset=spcdnew==sppcode,start=list(a0=a00, b1=b10, b2=b20))

   snlfit<-summary(nlfit)

  maxy<-10*ceiling(max(tree$HT[tree$spcdnew==sppcode])/10)
```

```
  maxx<-ceiling(max(tree$DIA[tree$spcdnew==sppcode]))

  dummy<-seq(0,maxx,.1)


plot(tree$DIA[tree$spcdnew==sppcode],tree$HT[tree$spcdnew==sppcode],xla
b='',ylab='', main=name,ylim=c(0,maxy),xlim=c(0,maxx),col=colpoint)

lines(dummy,4.5+snlfit$par[1,1]*(1-exp(snlfit$par[2,1]*dummy))^
snlfit$par[3,1],col=coline,lwd=2)

}
```

Finally we applied this model to all the species and created plots with the results.

```
layout(matrix(c(0,0,0,0,0,0,1,2,3,0,0,4,5,6,0,0,7,8,9,0,0,10,11,12,0,0,
0,0,0,0),6,5,byrow=T),  # 0 creates a region but does not draw a plot #

       widths=c((0.2),1,1,1,(0.1)),

       heights=c((0.2),1,1,1,1,(0.2)))

layout.show(12)

plotfit(1100,namespp[1,2],'red','black',200,-.01,1)

plotfit(1501,namespp[2,2],'red','black',202,-.01,1)

plotfit(1502,namespp[3,2],'red','black',187,-.01,1)

plotfit(1503,namespp[4,2],'red','black',159,-.01,1)

plotfit(1900,namespp[5,2],'red','black',106,-.01,1)

plotfit(2000,namespp[6,2],'red','black',178,-.01,1)

plotfit(2200,namespp[7,2],'red','black',225,-.01,1)

mtext('Tree height (ft)',at=350,line=5,side=2,cex=1.2)

plotfit(4100,namespp[8,2],'red','black',200,-.01,1)

plotfit(4200,namespp[9,2],'red','black',150,-.01,1)

plotfit(6400,namespp[12,2],'red','black',150,-.01,1)

plotfit(7200,namespp[14,2],'red','black',100,-.01,1)

plotfit(7300,namespp[15,2],'red','black',100,-.01,1)

mtext('Tree diameter (in)',at=-60,line=5,side=1,cex=1.2)
```

APPENDIX II. CURRENT TREE SPECIES

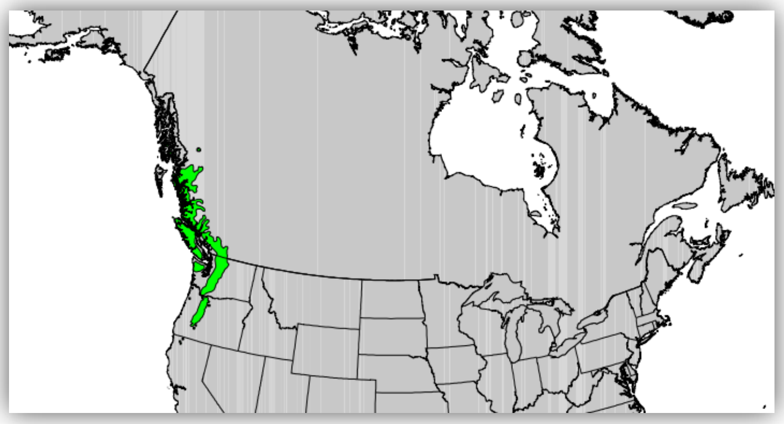
In this appendix the main tree species of the Pacific Coast are exposed (USDA, 1965, First edition) with the representations of tree species range maps (Little, 1966-1978).

1. Pacific silver fir (*Abies amabilis*)

Pacific silver fir, also known as silver fir and Cascades fir, has a gray trunk, a rigid, symmetrical crown, and lateral branches perpendicular to the stem. It contrasts strikingly with the more limber crowns, acute branch angles, and generally darker trunks of its common associates Douglas-fir *(Pseudotsuga menziesii),* western hemlock *(Tsuga heterophylla),* and mountain hemlock *(T. mertensiana).*

Pacific silver fir is found in southeastern Alaska, in coastal British Columbia and Vancouver Island, and along the western and upper eastern slopes of the Cascade Range in Washington and Oregon. It also grows throughout the Olympic Mountains and sporadically in the Coast Ranges of Washington and northern Oregon. Appears at a few locations in the Klamath Mountains of northwestern California too. The major portion of its range lies between latitudes 43° and 55° N.

Western hemlock is a common associate throughout most of the range of Pacific silver fir, in the Abies amabilis zone and portions of the Tsuga heterophylla zone. Noble fir (Abies procera) is an important associate in southern Washington and northern Oregon.



2. Santa Lucia fir, bristelecone fir (*Abies concolor*)

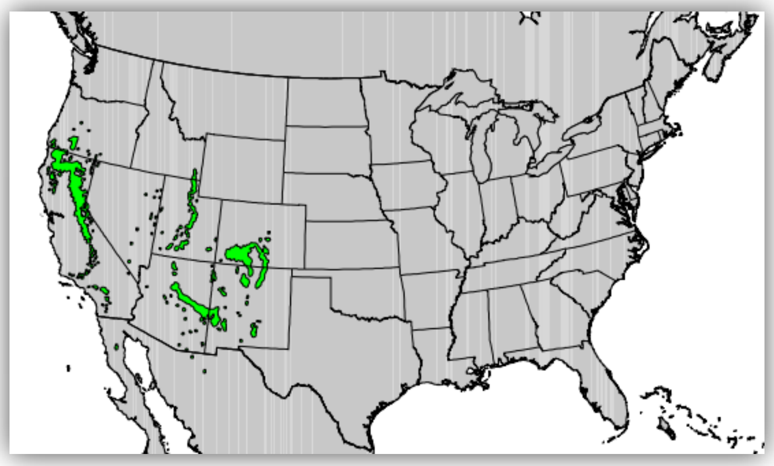
White fir reaches its best development and maximum size in the central Sierra Nevada of California, where the record specimen is 58.5 m (192 ft) tall and measures 271 cm

(106.6 in) in d.b.h. Large but not exceptional specimens, on good sites, range from 40 to 55 m (131 to 180 ft) tall and from 99 to 165 cm (39 to 65 in) in d.b.h. in California and southwestern Oregon and to 41 m (134 ft) tall and 124 cm (49 in) in d.b.h. in Arizona and New Mexico.

Long considered undesirable for timber, white fir *(Abies concolor)* is finally being recognized as a highly productive, valuable tree species.

The native range of white fir extends from the mountainous regions of the Pacific coast to central Colorado, and from central Oregon and southeastern Idaho to northern Mexico.

The most common associates of California white fir in the mixed conifer forests of California and Oregon include grand fir (Abies grandis), Pacific madrone (Arbutus menziesii), tanoak (Lithocarpus densiflorus), incense-cedar (Libocedrus decurrens), ponderosa pine (Pinus ponderosa), lodgepole pine (P. contorta), sugar pine (P. lambertiana), Jeffrey pine (P. jeffreyi), Douglas-fir (Pseudotsuga menziesii), and California black oak (Quercus kelloggii). In the central Sierra Nevada, white fir is a major associate of the relatively rare giant sequoia (Sequoiadendron giganteum). Species mix varies with elevation, site, and latitude. White fir is more abundant on the cooler, wetter sites.

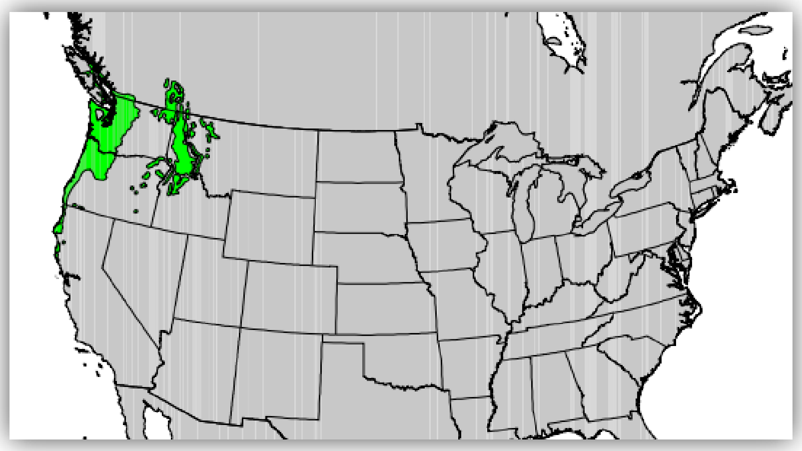


3. Grand fir (*Abies grandis*)

Also called lowland white fir, balsam fir, or yellow fir, is a rapid-growing tree that reaches its largest size in the rain forest of the Olympic Peninsula of Washington. One tree in that area measures 200 cm (78.9 in) in d.b.h., 70.4 m (231 ft) tall, and has a crown spread of 14 m (46 ft).

Grand fir grows in the stream bottoms, valleys, and mountain slopes of northwestern United States and southern British Columbia. Its wide geographical distribution is from latitude 51° to 39° N. and from longitude 125° to 114° W. In the Pacific coast region it grows in southern British Columbia mainly on the lee side of Vancouver Island and the adjacent mainland, in the interior valleys and lowlands of western Washington and Oregon, and in northwestern California as far south as Sonoma County. The range in the continental interior extends from the Okanogan and Kootenay Lakes in southern British Columbia south through eastern Washington, northern Idaho, western Montana west of the Continental Divide, and northeastern Oregon.

Grand fir is either a seral or climax species in different forest types within its range. On moist sites it grows rapidly enough to compete with other seral species in the dominant overstory. On dry sites it becomes a shade-tolerant understory and eventually assumes dominance as climax conditions are approached.



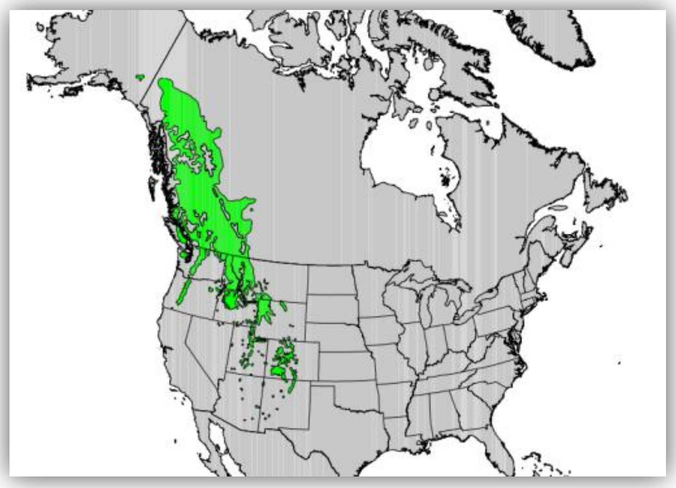
4. Subalpine fir (*Abies lasiocarpa*)

The smallest of eight species of true fir indigenous to the western United States, is distinguished by the long, narrow conical crown terminating in a conspicuous spikelike point.

Subalpine fir is a widely distributed North American fir. Its range extends from 32° N. latitude in Arizona and New Mexico to 64° 30 N. in Yukon Territory, Canada. Along the Pacific coast, the range extends from southeastern Alaska, south of the Copper River Valley (lat. 62° N.), the northwestern limit; east to central Yukon Territory (lat. 64° 30' N.), the northern limit; south through British Columbia along the east slopes of the Coast Range to the Olympic Mountains of Washington, and along both slopes of the Cascades to southern Oregon. It is not found on the west slopes of the Coast Range in southern British Columbia or along the Coast Range in Washington and Oregon, but it does occur on Vancouver Island. It is also found locally in northeastern Nevada and northwestern California. Except where noted above, subalpine fir is a major component of high elevation Pacific Northwest forests.

In the Rocky Mountain region, subalpine fir extends from the interior valleys of British Columbia west of the Continental Divide and south of the Peace River (lat. 55° N.), south along the high elevations of the Rocky Mountain system to southern New Mexico and Arizona. In the north, its range extends from the high mountains of central British Columbia, western Alberta, northeastern Washington, northeastern Oregon, Idaho, Montana, to the Wind River Mountains of western Wyoming. In Utah, it commonly occurs in the Uinta and Wasatch Mountains, but is less abundant on the southern plateaus. The range extends from southern Wyoming, through the high mountains of Colorado and northern New Mexico, and westward through northeastern Arizona to the San Francisco Mountains. Subalpine fir is a major component of the high-elevation forests of the Rocky Mountains.

Corkbark fir is found mixed with subalpine fir on scattered mountains in southwestern Colorado; northern, western, and southwestern New Mexico; and in the high mountains of Arizona.



5. Lodgepole pine (*Pinus contorta*)

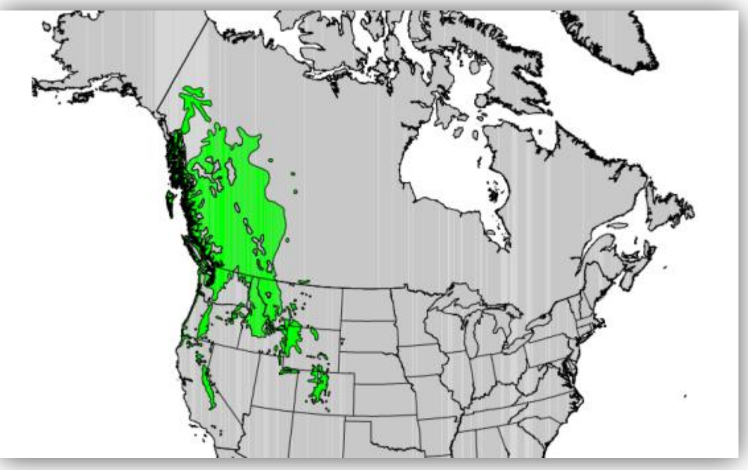
Lodgepole pine *(Pinus contorta)* is a two-needled pine of the subgenus *Pinus.* The species has been divided geographically into four varieties: *P. contorta* var. *contorta,* the coastal form known as shore pine, coast pine, or beach pine; *P. contorta* var. *bolanderi,* a Mendocino County White Plains form in California called Bolander pine; *P. contorta* var. *murrayana* in the Sierra Nevada, called Sierra lodgepole pine or tamarack pine; and *P. contorta* var. *latifolia,* the inland form often referred to as Rocky Mountain lodgepole pine or black pine. Although the coastal form grows mainly between sea level and 610 m (2,000 ft), the inland form is found from 490 to 3660 m (1,600 to 12,000 ft).

Lodgepole pine is a ubiquitous species with wide ecological amplitude. It grows throughout the Rocky Mountain and Pacific coast regions, extending north to about latitude 64° N. in the Yukon Territory and south to about latitude 31° N. in Baja California, and west to east from the Pacific Ocean to the Black Hills of South Dakota. Forests dominated by lodgepole pine cover some 6 million ha (15 million acres) in the Western United States and some 20 million ha (50 million acres) in Canada.

Lodgepole pine grows both in extensive, pure stands, and in association with many western conifers. The forest cover type Lodgepole Pine exists as a pure (80 percent or more) component of basal area stocking, as a majority (50 percent or more), or as a plurality (20 percent or more). The cover type includes all recognized subspecies of *Pinus contorta.*

Lodgepole pine, with probably the widest range of environmental tolerance of any conifer in North America, grows in association with many plant species. The lodgepole pine forest type is the third most extensive commercial forest type in the Rocky Mountains.

Lodgepole pine's successional role depends upon environmental conditions and extent of competition from associated species. Lodgepole pine is a minor seral species in warm, moist habitats and a dominant seral species in cool dry habitats. It is often persistent even on cool and dry sites and can attain edaphic climax at relatively high elevations on poor sites. Fire regimes have played a role in this successional continuum, especially where repeated fires have eliminated a seed source for other species.



6. Jeffrey pine (*Pinus jeffreyi*)

Jeffrey pine was first classified as a variety of ponderosa pine. These western yellow pines produce wood of identical structure and quality and are closely related taxonomically. Jeffrey pine is distinct chemically, ecologically, and physiologically and is readily distinguished from ponderosa pine on the basis of bark, leader, needle, bud, and cone morphology.

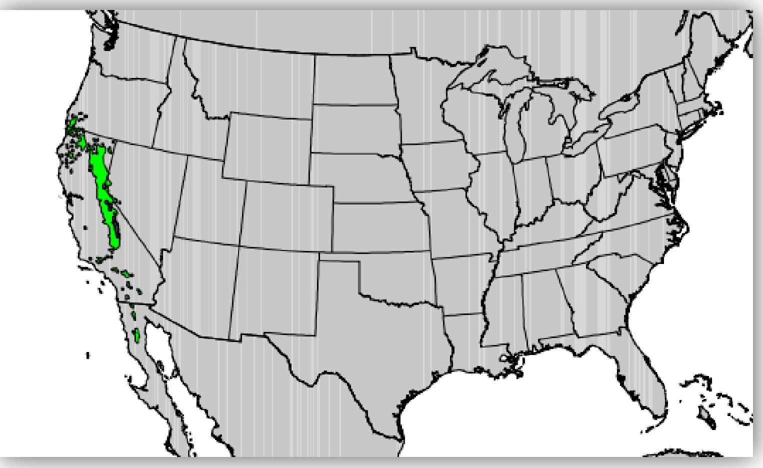
Primarily a California species, Jeffrey pine ranges north through the Klamath Mountains into southwestern Oregon, across the Sierra Nevada into western Nevada, and south in the Transverse and Peninsular Ranges into northern Baja California. This distribution is intimately linked with edaphic factors in the northwest portion of the range and strongly reflects climatic and elevational factors in the northeast, central, and southern portions.

Incense-cedar *(Libocedrus decurrens) is* the most widespread associate of Jeffrey pine on ultramafic soils. Locally prominent are Douglas-fir *(Pseudotsuga menziesii),* Port-Orford-cedar *(Chamaecyparis lawsoniana),* ponderosa pine, sugar pine *(Pinus lambertiana),* western white pine *(P. monticola),* knob-cone pine *(P. attenuata),* Digger pine *(P. sabiniana),* and Sargent cypress *(Cupressus sargentii).* Above 1600 m (5,250 ft) in the Klamath Mountains, North Coast Range, and northern Sierra Nevada, Jeffrey pine shares various soils and sites with California red fir *(Abies magnifica),* white fir *(A. concolor),* sugar pine, incense-cedar, western white pine, and Sierra lodgepole pine *(Pinus contorta* var. *murrayana).*

South of the Pit River in northeastern California and on the east side of the Cascade Range in southwestern Oregon and northern California, Jeffrey and ponderosa pines form extensive forests and usually intermingle in both closed and open, park like stands. Jeffrey pine forests range widely from 1520 to 2130 m (5,000 to 7,000 ft) of elevation in the northern Sierra Nevada, and from 1830 to 2900 m (6,000 to 9,500 ft) in the central and southern Sierra Nevada. Ponderosa pine, sugar pine, white fir, incense-cedar, California red fir, western white pine, lodgepole pine, and western juniper *(Juniperus occidentalis)* all mix in locally, but few of them join Jeffrey pine on south slopes and granitic soils.

Jeffrey pine is the dominant yellow pine in forests east of the Sierra Nevada crest and in the Transverse and Peninsular Ranges into Baja California. In the Sierra San Pedro Martir, it ranges from 1830 to 3050 m (6,000 to 10,000 ft) and shares the southern limits of sugar pine, white fir, incense-cedar, and lodgepole pine.

Jeffrey pine forests constitute one of the more unusual forest cover types in western North America, because Jeffrey pine has wide edaphic and elevational ranges in diverse physiographic regions.



7. Ponderosa pine (*Pinus ponderosa*)

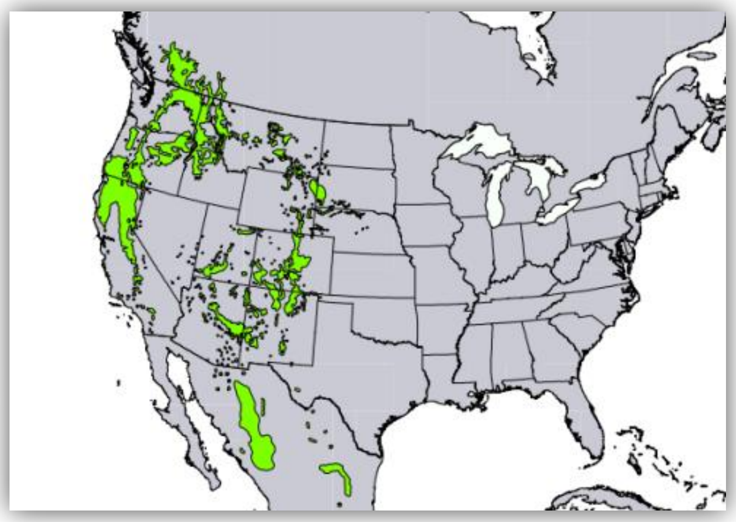
Ponderosa pine, also called western yellow pine, is one of the most widely distributed pines in western North America. A major source of timber, ponderosa pine forests are also important as wildlife habitat, for recreational use, and for esthetic values. Within its extensive range, two varieties of the species currently are recognized: *Pinus ponderosa* var. *ponderosa* (Pacific ponderosa pine) and var. *scopulorum* (Rocky Mountain ponderosa pine).

Pacific ponderosa pine (var. *ponderosa)* ranges from latitude 52° N. in the Fraser River drainage of southern British Columbia, south through the mountains of Washington, Oregon, and California, to latitude 33° N. near San Diego. In the northeast part of its range it extends east of the Continental Divide to longitude 110° W. in Montana, and south to the Snake River Plain, in Idaho.

Ponderosa pine can be either a climax or a seral species. It is a climax species at the lower limits of the coniferous forests, and a seral species in higher elevation mesic forests where more competitive conifers are capable of growing. In climax forests, ponderosa pine stands often contain many small, even-aged groups rather than a true uneven-aged structure.

Fires have had a profound effect on the distribution of ponderosa pine. Although the seedlings are readily killed by fire, larger trees possess thick bark, which offers effective protection from fire damage. Competing tree species, such as grand fir *(Abies grandis)* and Douglas-fir, are considerably less fire tolerant, especially in the sapling and pole size classes. Ponderosa pine, therefore, was able to maintain its position as a dominant seral species on large areas of middle-elevation forests in the West. Because of successful fire control during the past 50 years, many of these stands have developed understories of Douglas-fir and true firs. Type conversion has been accelerated by harvest of the ponderosa pine, leaving residual stands composed of true fir, Douglas-fir or lodgepole pine *(Pinus contorta* var. *latifolia)*. In the Pacific Northwest, forest cover types on about 2 million ha (5 million acres) are believed to have changed in the last 25 years.

Ponderosa pine is an integral component of three forest cover types in the West: Interior Ponderosa Pine, Pacific Ponderosa Pine-Douglas-Fir, and Pacific Ponderosa Pine. Interior Ponderosa Pine is the most widespread type, covering most of the range of the species from Canada to Mexico, and from the Plains States to the Sierra Nevada, and the east side of the Cascade Mountains. Ponderosa pine is also a component of 65 percent of all western forest cover types south of the boreal forest.



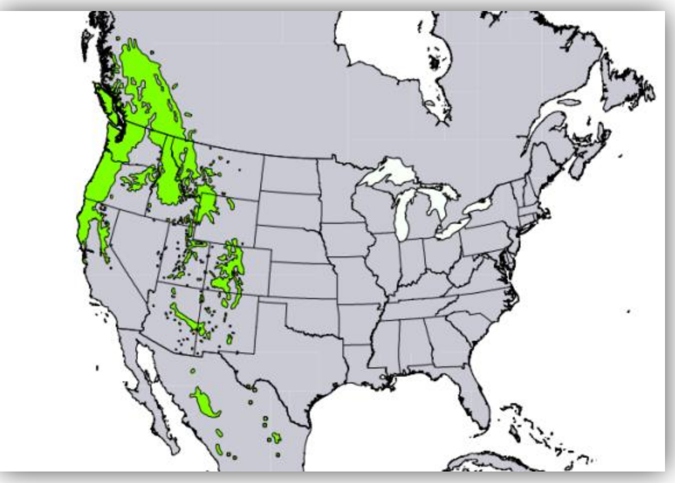
8. Douglas-fir (*Pseudotsuga menziesii*)

Douglas-fir, also called red-fir, Oregon-pine, Douglas-spruce, is one of the world's most important and valuable timber trees. It has been a major component of the forests of western North America since the mid-Pleistocene. Although the fossil record indicates that the native range of Douglas-fir has never extended beyond western North America, the species has been successfully introduced in the last 100 years into many regions of the temperate forest zone. Two varieties of the species are recognized: *P. menziesii* (Mirb.) Franco var. *menziesii,* called coast Douglas-fir, and *P. menziesii* var. *glauca* (Beissn.) Franco, called Rocky Mountain or blue Douglas-fir.

The latitudinal range of Douglas-fir is the greatest of any commercial conifer of western North America. Its native range, extending from latitude 19° to 55° N., resembles an inverted V with uneven sides. From the apex in central British Columbia, the shorter arm extends south along the Pacific Coast Ranges for about 2200 km (1,367 mi) to latitude 34° 44' N., representing the range of the typical coastal or green variety, *menziesii*; the longer arm stretches along the Rocky Mountains into the mountains of central Mexico over a distance of nearly 4500 km (2,796 mi), comprising the range of the other recognized variety, *glauca*- Rocky Mountain or blue. Nearly pure stands of Douglas-fir continue south from their northern limit on Vancouver Island through western Washington, Oregon, and the Klamath and Coast Ranges of northern California as far as the Santa Cruz Mountains. In the Sierra Nevada, Douglas-fir is a common part of the mixed conifer forest as far south as the Yosemite region. The range of Douglas-fir is fairly continuous through northern Idaho, western Montana, and northwestern Wyoming. Several outliers are present in Alberta and the eastern-central parts of Montana and Wyoming, the largest being in the Bighorn Mountains of Wyoming. In northeastern Oregon, and from southern Idaho south through the mountains of Utah, Nevada, Colorado, New Mexico, Arizona, extreme western Texas, and northern Mexico, the distribution becomes discontinuous.

Periodic recurrence of catastrophic wildfires created vast, almost pure stands of coastal Douglas-fir throughout its range north of the Umpqua River in Oregon. Although logging has mainly eliminated the original old-growth forest, clearcutting combined with slash burning has helped maintain Douglas-fir as the major component in second-growth stands. Where regeneration of Douglas-fir was only partially successful or failed, red alder *(Alnus rubra)* has become an associate of Douglas-fir or has replaced it altogether.

Toward the fog belt of the Pacific coast, Douglas-fir gives way to Sitka spruce *(Picea sitchensis),* western hemlock *(Tsuga heterophylla),* and western redcedar. The variety menziesii is a major component of four forest cover types: Pacific Douglas-Fir, Douglas-Fir-Western Hemlock, Port Orford-Cedar, and Pacific Ponderosa Pine-Douglas-Fir.



9. Western redcedar (*Thuja plicata*)

Western redcedar *(Thuja plicata),* also called Pacific redcedar, giant-cedar, arborvitae, canoe-cedar, and shinglewood, is the only *Thuja* species native to western North America. Extant redcedar volumes are estimated to be 824 million m³ (29 billion ft³) in British Columbia and 228 million m³ (8 billion ft³) in the United States. Most of this volume is in mature trees, which have tapered, often-fluted bases, drooping branches, thin fibrous bark, and small scale like leaves arrayed in flat sprays. Many have forked tops. They often reach ages of 800 to 1,000 years. The wood is valuable and extensively used in a wide variety of products.

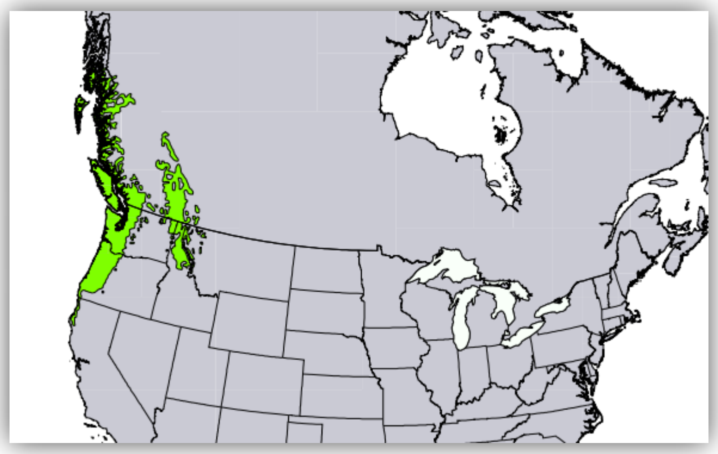
Western redcedar grows along the Pacific coast from Humboldt County, CA (lat. 40° 10' N.), to the northern and western shores of Sumner Strait in southeastern Alaska (lat. 56° 30' N.). In California, it is common only in the lower Mad River drainage and the wet region south of Ferndale in Humboldt County; it is found elsewhere only in isolated stands in boggy habitats. North of the California-Oregon border, the coastal range broadens to include the western slopes of the Cascade Range north of Crater Lake and the eastern slopes north of about latitude 44° 30' N. Optimal growth and development of western redcedar are achieved near the latitudinal center of its range-Washington's Olympic Peninsula.

North of the Olympic Peninsula and Vancouver Island, the coastal range narrows again and is restricted to the Coast Ranges and offshore islands. A few scattered stands are found between the Coast Ranges and the Selkirk Mountains near the southern border of British Columbia, but redcedar's coastal range is essentially isolated from its interior range.

The interior range extends south from the western slope of the Continental Divide at latitude 54° 30' N. in British Columbia through the Selkirk Mountains into western Montana and northern Idaho. The southern limit is in Ravalli County, MT (lat. 45° 50' N.). With the possible exception of a few trees east of the Continental Divide near the upper end of St. Mary Lake, Glacier County, the eastern limit of the range of redcedar is near Lake McDonald in Glacier National Park, MT.

Pure stands of western redcedar cover some small areas, but it is usually associated with other tree species. Along the coast these include black cottonwood *(Populus trichocarpa),* bigleaf maple *(Acer macrophyllum),* western hemlock, mountain hemlock *(Tsuga mertensiana),* Sitka spruce, western white pine *(Pinus monticola),* lodgepole (shore) pine *(P. contorta),* Port Orford-cedar *(Chamaecyparis lawsoniana),* Alaska-cedar *(C. nootkatensis),* incensecedar *(Libocedrus decurrens),* Douglas-fir, grand fir, Pacific silver fir *(Abies amabilis),* red alder *(Alnus rubra),* Pacific madrone *(Arbutus menziesii),* and Pacific yew *(Taxus brevifolia).* Several of these species (black cottonwood, western hemlock, western white pine, Douglas-fir, grand fir, and Pacific yew) are also associated with western redcedar in the interior. Subalpine fir *(Abies lasiocarpa),* western larch *(Larix occidentalis),* Engelmann spruce *(Picea engelmannii),* white spruce *(P. glauca),* lodgepole pine, and ponderosa pine are also associated with redcedar in the interior.

Redcedar is a major component of two forest cover types; Western Redcedar and Western Redcedar-Western Hemlock.



10. Western hemlock (*Tsuga heterophylla*)

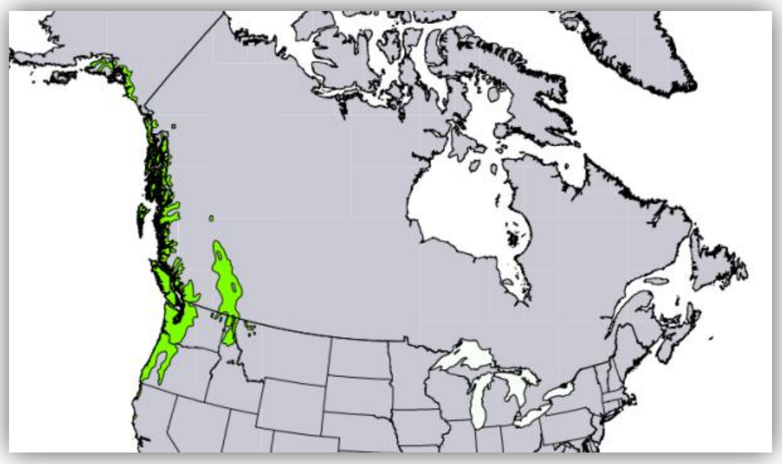
Western hemlock *(Tsuga heterophylla),* also called Pacific hemlock and west coast hemlock, thrives in humid areas of the Pacific coast and northern Rocky Mountains. Its potential for management as an efficient producer of fiber has long been recognized. It is an important browse species for deer and elk. Western hemlock provides an important part of the esthetic background for eight national parks, four each in the United States and Canada. It is a pioneer on many sites, yet it is commonly the climax dominant. Although western hemlock grows like a weed, it has a great versatility and potential for management.

Western hemlock is an important commercial tree species of the Pacific coast and northern Rocky Mountains. Along the Pacific coast, its range extends north along the Coast Ranges from central California to the Kenai Peninsula in Alaska, a distance of 3200 km (2,000 mi). It is the dominant species in British Columbia and Alaska along the Coast Mountains and on the coastal islands.

In land it grows along the western and upper eastern slopes of the Cascade Range in Oregon and Washington and the west side of the Continental Divide of the northern Rocky Mountains in Montana and Idaho north to Prince George, BC.

Western hemlock is either a major or a minor component in at least 20 forest cover types. Tree associates specific to the coast include, for example, Pacific silver fir *(Abies amabilis),* noble fir *(A. procera),* red alder *(Alnus rubra),* giant chinkapin *(Castanopsis chrysophylla),* etc. Associates occurring in both the Pacific coast and Rocky Mountain portions of its range include grand fir *(Abies grandis),* subalpine fir *(A. lasiocarpa),* western larch *(Larix occidentalis),* white spruce *(P. glauca),* or lodgepole pine *(Pinus contorta)* for example.

Western hemlock is a component of the redwood forests on the coasts of northern California and adjacent Oregon. In Oregon and western Washington, it is a major constituent of the *Picea sitchensis, Tsuga heterophylla,* and *Abies amabilis* Zones and is less important in the *Tsuga mertensiana* and Mixed-Conifer Zones.



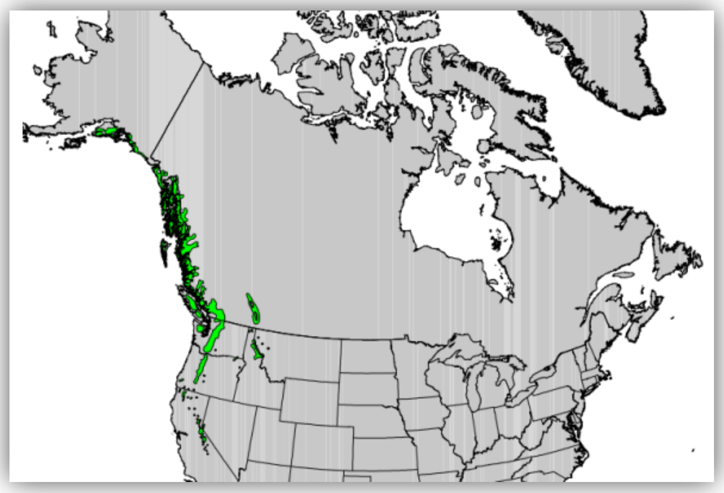
11. Mountain hemlock (*Tsuga mertensiana*)

Mountain hemlock *(Tsuga mertensiana)* is usually found on cold, snowy subalpine sites where it grows slowly, sometimes attaining more than 800 years in age. Arborescent individuals that have narrowly conical crowns until old age (300 to 400 years). Uses of its moderately strong, light-colored wood include small-dimension lumber and pulp.

Mountain hemlock grows from Sequoia National Park in California (lat. 36° 38' N.) to Cook Inlet in Alaska (lat. 61° 25' N.). It grows along the crest of the Sierra Nevada in California; the Cascade Range in Oregon; the Cascade Range and Olympic Mountains in Washington; the northern Rocky Mountains in Idaho and western Montana; the Insular, Coast, and Columbia Mountains in British Columbia; and in southeast and south-central Alaska.

Mountain hemlock usually grows in mixture with other trees, and it has many associates, as is evident from the large number of forest types in which it is found. Though pure stands are less common than mixed stands, there are extensive pure stands of mountain hemlock in Alaska and in the central high Cascades of Oregon.

One of the most widespread mountain hemlock communities is the mountain hemlock-Pacific silver fir/big huckleberry *(Tsuga mertensiana-Abies amabilis/Vaccinium membranaceum)* type found in British Columbia and the Oregon and Washington Cascades. In British Columbia, the understory is dominated by deciduous ericaceous shrubs: Cascades azalea *(Rhododendron albiflorum),* Alaska huckleberry *(Vaccinium alaskaense),* rustyleaf menziesia *(Menziesia ferruginea),* ovalleaf huckleberry *(Vaccinium ovalifolium),* and big huckleberry. Also included are strawberryleaf blackberry *(Rubus pedatus)* and several mosses. Silver fir and Alaska-cedar *(Chamaecyparis nootkatensis)* are common tree associates in this community in coastal areas, and subalpine fir *(Abies lasiocarpa)* and Engelmann spruce *(Picea engelmannii)* are common associates in inland areas.



12. Red alder (*Alnus rubra*)

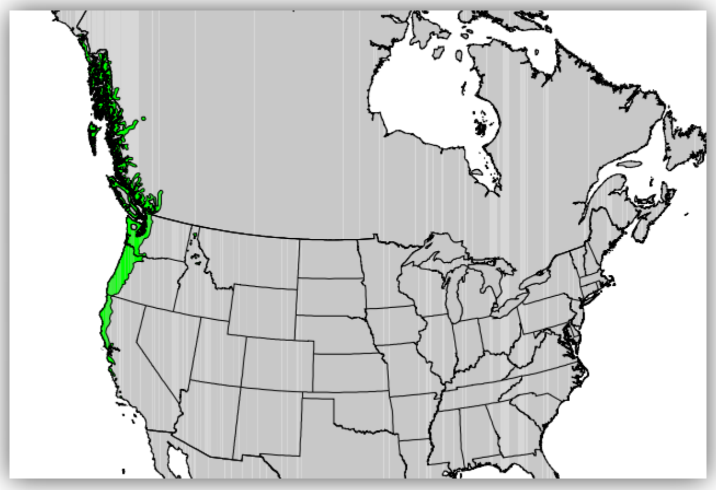
Red alder, also called Oregon alder, western alder, and Pacific coast alder, is the most common hardwood in the Pacific Northwest. It is a relatively short-lived, intolerant pioneer with rapid juvenile growth. The species is favored by disturbance and often increases after logging and burning. Because the commercial value of alder has traditionally been lower than that of its associated conifers, most forest managers have tried to eliminate the species from conifer stands. On the other hand, red alder is the only commercial tree species west of the Rocky Mountains with the capability to fix atmospheric nitrogen, and the species is now being considered for deliberate use in some management systems.

Red alder is most often observed as a lowland species along the northern Pacific coast. Its range extends from southern California (lat. 34° N.) to southeastern Alaska (60° N.). Red alder is generally found within 200 km (125 mi) of the ocean and at elevations below 750 m (2,400 ft). It seldom grows east of the Cascade Range in Oregon and Washington or the Sierra Nevada in California, although several isolated populations exist in northern Idaho.

Red alder grows in both pure and mixed stands. Pure stands are typically confined to stream bottoms and lower slopes. Red alder is, however, much more widely distributed as a component of mixed stands. It is a major component of the forest cover type Red Alder and occurs as a minor component in most of the other North Pacific cover types.

Common tree associates are Douglas-fir *(Pseudotsuga menziesii),* western hemlock *(Tsuga heterophylla),* western redcedar *(ThuJa plicata),* grand fir *(Abies grandis),* Sitka spruce *(Picea sitchensis),* black cottonwood *(Populus trichocarpa),* bigleaf maple *(Acer macrophyllum),* and willow *(Salix spp.).*

Occasional tree associates include cascara buckthorn *(Rhamnus purshiana),* Pacific dogwood *(Cornus nuttallii),* and Oregon ash *(Fraxinus latifolia).* Western paper birch *(Betula papyrifera* var. *commutata)* is an occasional associate in the northern portion of the range of alder, and redwood *(Sequoia semperuirens)* in the southern portion.



13. Tanoak (*Lithocarpus densiflorus*)

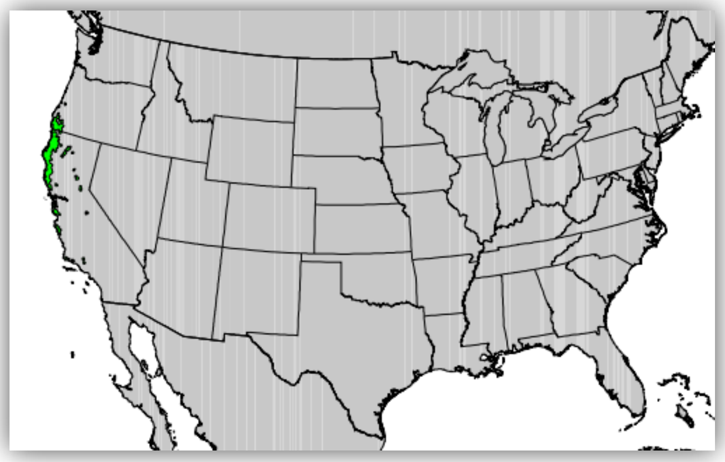
Tanoak *(Lithocarpus densiflorus),* also called tanbark-oak, is an evergreen hardwood that, with other species in the genus, is considered a link between the chestnut, *Castanea,* and the oak, *Quercus.* Tanoak has flowers like the chestnut and acorns like the oak. This medium-sized tree grows best on the humid moist slopes of the seaward coastal ranges. It usually occurs in a complex mixture with conifers and other hardwoods, but often forms pure even-aged stands. The wood is hard, strong, and fine-grained. Tanoak is designated a commercial species in California. Current major uses are for fuel and pulp. The acorns are a valuable food source for many kinds of wildlife.

A disjunct stand slightly north of the Umpqua River in southwestern Oregon has been reported as the northernmost limit of tanoak's natural range. The general northern limit of tanoak in the Coast Ranges, however, is farther south in the Coquille River drainage. Its eastern limit in Oregon extends from west of Roseburg to Grants Pass, and then southwesterly into the Applegate River drainage. Tanoak's range stretches southward through the Coast Ranges in California to the Santa Ynez Mountains north and east of Santa Barbara, CA. The range also extends northeastward from the Humboldt Bay region to the lower slopes of Mount Shasta, then intermittently southward along the western slopes of the Sierra Nevada as far as Mariposa County. In the Sierra Nevada, tanoak is most common between the Feather and American Rivers.

Tanoak grows within the life zones classified as the Canadian and Transition. It is the most abundant hardwood species in timber stands of the Coast Ranges of California and southwestern Oregon. Tanoak is a common component in the following forest cover types: Redwood, Pacific Ponderosa Pine, Pacific Ponderosa Pine-Douglas-Fir, Sierra Nevada Mixed Conifer, and California Coast Live Oak. It is a particularly important component of Pacific Douglas-Fir and Douglas-Fir-Tanoak-Pacific Madrone.

The principal body of tanoak is a broad band along the inland side of the redwood belt. Here tanoak sometimes forms almost pure stands. More often it is an understory tree with Douglas-fir or is a component of hardwood stands or mixed hardwood-conifer forests. The most common hardwood associated with tanoak is Pacific madrone. Other frequent hardwood associates include giant chinkapin *(Castanopsis chrysophylla),* canyon live oak *(Quercus chrysolepis),* California black oak *Q. kelloggii),* and California-laurel *(Umbellularia californica).* Tanoak is found most often with Douglas-fir and redwood. Other common conifer associates are California white fir *(Abies concolor* var. *lowiana),* Sitka spruce *(Picea sitchensis),* sugar pine *(Pinus lambertiana),* ponderosa pine *(P. ponderosa* var. *ponderosa),* California torreya *(Torreya californica),* and western hemlock *(Tsuga heterophylla).*

A large variety of shrubs, forbs, grasses, sedges, and ferns are also associated with tanoak. Generally these plants are not abundant on forested land, but, with tanoak sprouts, often become aggressive on burned or cutover areas. Among the most common shrubs are blueblossom *(Ceanothus thyrsiflorus),* California hazel *(Corylus cornuta* var. *californica),* salal *(Gaultheria shallon),* Pacific bayberry *(Myrica californica),* Pacific rhododendron *(Rhododendron macrophyllum),* flowering currant *(Ribes sanguineum),* thimbleberry *(Rubus parviflorus),* western poison-oak *(Toxicodendron diversilobum),* and California huckleberry *(Vaccinium ovatum).*



13. Canyon live oak (*Quercus chrysolepis*)

Canyon live oak *Quercus chrysolepis),* also called canyon oak, goldcup oak, live oak, maul oak, and white live oak, is an evergreen species of the far West, with varied size and form depending on the site. In sheltered canyons, this oak grows best and reaches a height of 30 in (100 ft). On exposed mountain slopes, it is shrubby and forms dense thickets. Growth is slow but constant, and this tree may live for 300 years. The acorns are important as food to many animals and birds. The hard dense wood is shock resistant and was formerly used for wood-splitting mauls. It is an excellent fuel wood and makes attractive paneling. Canyon live oak is also a handsome landscape tree.

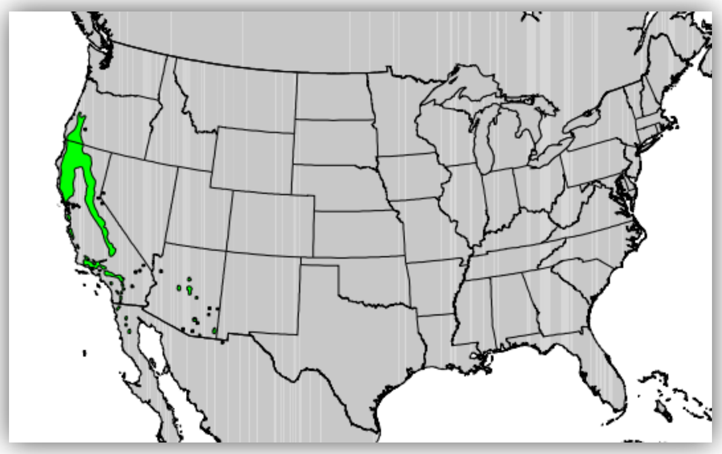
Canyon live oak is found in the Coast Ranges and Cascade Range of Oregon and in the Sierra Nevada in California, from latitude 43° 85° N. in southern Oregon to latitude 31° 00° N. in Baja California, Mexico. In southern Oregon, it grows on the interior side of the Coast Ranges and on the lower slopes of the Cascade Range. It grows throughout the Klamath Mountains of northern California, along the coastal mountains and the western slopes of the Sierra Nevada, and east of the redwood *(Sequoia sempervirens)* forest on the coast, except in the King Range, where it grows close to the coast. In central and southern California, canyon live oak is found on or near the summits of mountains. Scattered populations appear in the mountains of southern Nevada, Arizona, and northwestern Chihuahua, Mexico.

In southwestern Oregon, canyon live oak is primarily associated with Douglas-fir, tanoak, giant chinkapin *(Castanopsis chrysophylla),* and Pacific madrone *(Arbutus menziesii)* in the mixed evergreen forests. In these forests it is a codominant tree and a shrub in the *Pseudotsuga menziesii-Quercus chrysolepis-Lithocarpus densiflorus/Quercus chrysolepis-Lithocarpus densiflorus* climax community type.

In the Klamath region of northern California, canyon live oak is an occasional small tree or shrub throughout the *Abies concolor* zone of the montane or mixed conifer forest of the interior side of the Coast Ranges and Klamath Mountains. In the *Abies concolor /Arbutus menziesii/Corylus cornuta* type, canyon live oak is a codominant lower canopy tree under ponderosa pine, sugar pine, and white fir *(Abies concolor).*

In the Coast Ranges of northern California, canyon live oak is a major component of the mixed evergreen forest or Douglas-Fir-Tanoak-Pacific Madrone. In these forests, it is associated with bigleaf maple, California-laurel, coast live oak *Quercus agrifolia),* Douglas-fir, madrone, and tanoak.

In the central Coast Ranges of California, canyon live oak is a codominant in the mixed hardwood forests, associated with coast live oak, blue oak *(Quercus douglasii),* interior live oak *(Q. wislizeni),* California black oak *(Q. kelloggii),* madrone, tanoak, California laurel, and Digger pine *(Pinus sabiniana).* In this area, it also occurs in successional chaparral associated with Eastwood manzanita *(Arctostaphylos glandulosa).* At higher elevations, canyon live oak is dominant in the canyon live oak-Coulter pine forest.



APPENDIX III. INVENTORY WORK PHOTOS

All the photos are from USDA Forest Service.

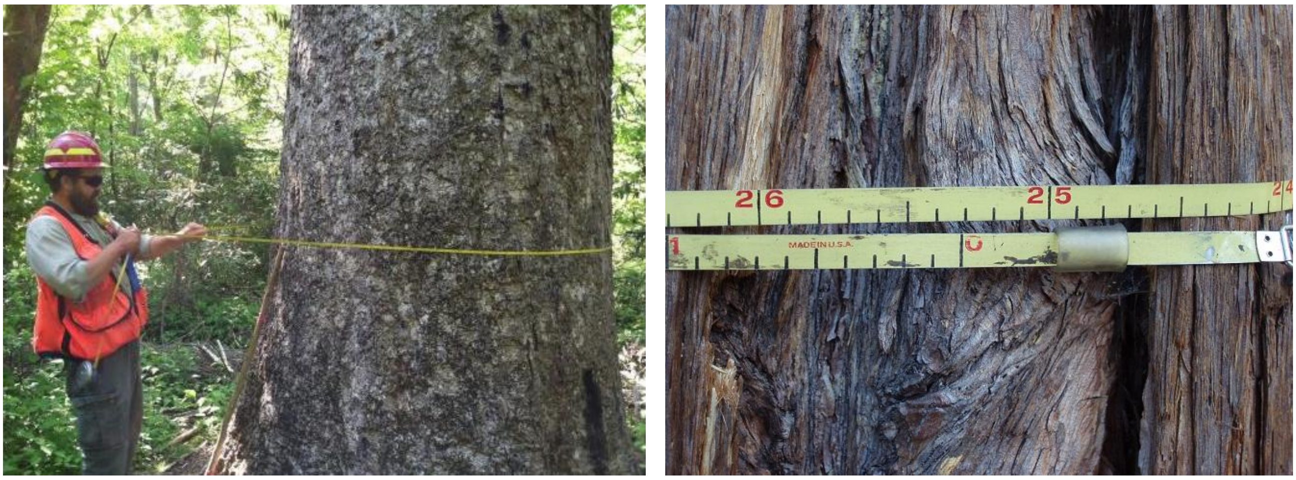


Figure 6. Measurement of the diameter, using a diameter tape wrapped around the main stem of the tree

Figure 7. Measuring height with a woodland stick

Figure 8. Measuring height with laser technologies

Figure 9. Measuring dead wood

APPENDIX IV. METRIC EQUIVALENCES

Table 8. Equivalence of measurement units

Length	
1 inch	2.54 centimeters (cm.)
0.1 feet	3.048 centimeters (cm.)
1 foot	0.3048 meter (m.)
1 mile	1.609 kilometers (km.)
1 centimeter (cm.)	.03 foot (ft.)
1 meter (m.)	3.2808 feet (ft.)
1 mile	5280 feet
Area	
1 acre	0.4 hectare (ha.) (approximately)
5 acres	2 hectares (ha.) (approximately)
1,000 acres	404.7 hectares (ha.)
1 hectare	2.471 acres (ac.)
2.5 hectares	6 acres (ac.) (approximately)
1 square mile	2.589 square kilometers
1 square kilometer	0.386 square miles
Volume	
1,000 cubic feet	28.3 meters (m3)
1 cubic foot per acre	0.07 cubic meter per hectare (m3/ha)
Condition Class Minimum Area	
0.4 hectares (1 acre)	4,000 square meters
	40 meters x 100 meters
	35 meter radius circle
1 acre	118 foot radius circle
	209 feet x 209 feet
	43,560 square feet