Forest Ecology and Management 432 (2019) 179–188

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Aboveground biomass equations for the predominant conifer species of the Inland Northwest USA

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ARTICLE INFO

Keywords:
Tree biomass equation systems
Inland northwest
Randomized branch sampling
Forest inventory

ABSTRACT

Assessment of aboveground biomass stocks in the coniferous forests of the inland northwest USA is important for timber, bioenergy, and carbon inventories, as well as for wildfire risk determination. In this study, individual tree biomass equation systems are developed for 7 regionally important conifer species using data from 470 felled trees sampled across 84 stands and spanning a range of diameters at breast height (1.37 m; dbh) running from 5 cm to 105 cm. The equation systems permit estimation of crown biomass components (i.e., foliage, dead branches, and live branches by size class) and stem components (abovestump stemwood and stembark), as well as compatible estimates of (sub)totals. The systems draw on commonly collected inventory variables including dbh, tree height, and live crown length. All biomass components scaled approximately linearly with dbh on the logarithmic scale, but equation systems drawing on both dbh and height provided more accurate estimates for all species; systems drawing additionally on live crown length provided more accurate estimates still for all species but one. In line with previous work, incorporation of live crown length improved live crown component equations most, but also improved stem component equations for two species. Across species and systems, stem components and subtotals were most accurately estimated (mean absolute errors ~10%) while dead branch biomass estimation proved least tractable (mean absolute errors >50%). Overall, the reported biomass equation systems draw on the largest felled tree samples collected from the region, and provide the most comprehensive basis developed to date for regional forest biomass assessments over the inland northwest.

1. Introduction

The temperate coniferous forests of the inland northwest, a mountainous region of the USA encompassing parts of eastern Washington, northern Idaho, and western Montana, span a broad range of elevations and diverse climatic regimes. In the last century, management of this landscape was framed primarily by timber harvesting and wildfire suppression. These remain predominant activities across the region, though today fuels mitigation, bioenergy extraction, and carbon sequestration are also important forest management objectives. Crucial to the effectiveness and sustainability of all these activities is the ability to reliably assess forest biomass stocks. Biomass is of central interest in fuels and bioenergy assessments, has direct linkages to forest carbon inventory, and is increasingly being used a basis for the trading of merchantable wood products. Despite this, there are presently no comprehensive sets of aboveground biomass equations for the major conifer species of the region. The purpose of this research is to advance a set of such equations calibrated from regional felled tree data.

The most widespread and commercially important coniferous species in the inland northwest are Douglas-fir (*Pseudotsuga menziesii* var. *glauca*; PSME), lodgepole pine (*Pinus contorta*; PICO), ponderosa pine (*Pinus ponderosa*; PIPO), western larch (*Larix occidentalis*; LAOC), grand fir (*Abies grandis*; ABGR), subalpine fir (*Abies lasiocarpa*; ABLA), and Engelmann spruce (*Picea engelmannii*; PIEN). An extensive study of the biomass allometries of these 7 species (and 4 additional species) was conducted by Brown (1978). However, his study focused on crown biomass – no data were collected on stem components for trees with diameter at breast-height (dbh) above 10 cm. This focus was owing to the primary role of crown components in wildfire dynamics and to the fact that wood products in the inland northwest were traded almost exclusively on a volumetric basis at that time. Revisions to Brown's foliar biomass equations were made by Moeur (1981), and adjustments for a subset of the crown equations were proposed by Gray and Reinhardt (2003). Nonetheless, Brown's equation systems remain the standard basis for tree-level biomass determination in regional studies.

For analyses of a national or broader scope, the equations developed by Jenkins et al. (2003) (later revised by Chojnacky et al., 2014) have been applied to inventory data from inland northwest forests. Indeed, the USA's Forest Inventory & Analysis (FIA) program utilizes the former equations across the western USA, albeit only as a method for

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https://doi.org/10.1016/j.foreco.2018.09.009
Received 20 June 2018; Received in revised form 5 September 2018; Accepted 7 September 2018
0378-1127/

distributing biomass among tree components (Woodall et al., 2011). As Jenkins et al. emphasized, these equations were generalized in order to "provide a consistent basis for evaluating forest biomass across regional boundaries" (p. 13). The generalizations, including the aggregation of species into groups (e.g., all *Pinus* species for total mass determination; all conifer species for component biomass distribution) and the use of dbh as the sole predictor of biomass, ought to serve well in capturing overall trends and ensuring that estimates do not vary as a function of artificial boundaries (e.g., state lines). Yet these same generalizations also mean that the equations cannot account for variations in height-diameter ratios, crown ratios, or even species in many cases. Such variations are common within a region as diverse in growing conditions and management practices as the inland northwest.

Needed within the region are biomass equations that can accommodate these sources of variation and provide whole-tree and component estimates calibrated to the species and predominant growing conditions of the inland northwest. As shown by Case and Hall (2008), regionally-calibrated equations can provide biomass estimates with less bias and improved precision relative to generalized national-level equations, and with accuracy approaching that of localized equations. This can be achieved in part by confining the calibration data to the region (and species) of interest, but also by expanding the suite of predictor variables to include others commonly collected in regional inventories. In the inland northwest, height-diameter ratios can vary substantially as a function of stand density, and thus height is commonly recognized as an important variable for regional stem volume estimation (see e.g. Table 3 in Woodall et al., 2011). Likewise, live crown length can vary with stand density and development, and both empirical studies (Brown, 1978; Evert, 1985) and allometric scaling theory (Mäkelä and Valentine, 2006) support its use as an important predictor of crown biomass.

The primary objective of this research was to develop systems of biomass equations for the aboveground components of the major conifer species in the inland northwest, and to calibrate the systems using regional felled tree data. The systems are intended for use in forest inventory, and thus focus on trends in biomass distributions with respect to commonly measured inventory variables (dbh, total height, live crown length, and derived variables). A secondary objective was to compare the performance of biomass equation systems employing distinct subsets of tree-level predictor variables – specifically, systems employing only dbh and systems employing only dbh and height.

2. Materials & methodology

2.1. Stand and tree selection

Felled tree data were collected during the summers of 2009–2015. Collection protocols varied across years owing to evolving objectives and constraints, but followed the same general outline. Throughout the period, study stands were selected opportunistically across federal, state, tribal, and private lands with the aim of securing a sample of trees having broad geographic, climatic, and size distributions. Study stands were not confined to active or planned timber sales, but neither were such stands excluded; only stands thinned or treated within 5 years were categorically excluded.

Within selected stands, candidate sample trees were identified at one or more sample points. In most stands, sample points were located systematically on the universal transverse Mercator (UTM) grid at 50 m intervals, with points located no closer than 25 m to a road. In other stands, particularly active logging sites, points were located opportunistically, though still with a 50 m offset and 25 m road buffer. From 2009 to 2012, candidate sample trees were identified at each sample point using a 2.3 m^2/ha factor prism; up to two trees at each point were then selected for destructive biomass sampling. Final tree selection was generally made at random, but in some instances trees were selected purposively to broaden the species and size class distribution of the sample. From 2013 onward, only the latter strategy was used and up to 4 trees were purposively selected within the vicinity of a sample point. In all years, trees were selected for sampling only if they exhibited (i) dbh $\geqslant$ 5 cm; (ii) no obvious forking or broken/dead tops; and (iii) no obvious insect or disease damage. Once selected, sample trees were directionally felled so as to minimize branch entanglement and breakage. Total height and height to the base of the live crown were then measured. The base of the live crown was defined as the lowest point on the stem where at least two live branches separated by an angle of $\geqslant 90°$ were attached (USDA Forest Service, 2009, p. 42).

2.2. Estimation of stem biomass

The stem of a sample tree was defined as the largest diameter limb emanating from any forkings between a stump height of 30 cm from ground and an upper-stem diameter of 5 cm. All branches attached to the stem as well as the tree tip above an outside-bark diameter of 5 cm were treated as crown materials. Inside and outside bark diameter measurements were made along the length of each stem, and three or more discs were then cut between the ground line and the 5 cm top. Discs were drawn systematically with a random start except in a few stands where merchandizing restrictions required that the discs be taken at prescribed log lengths. Also, in 2013, felled trees were cut into segments at 0.15 m, 1.37 m, 2.44 m, and then every 2.44 m up the stem to the 5 cm top. The segments were weighed green in the field (wood and bark combined) before discs were extracted from the top or bottom. Discs were weighed and measured in the field, then weighed again after oven-drying at 105 °C to a constant mass. A detailed description of how the disc and stem measurements were combined to obtain individual tree stemwood and stembark biomass estimates (m_w and m_b, respectively; see Table 1) is provided in the supplementary materials (p. S1).

2.3. Estimation of crown biomass

Live crown biomass was assessed using aggregated randomized branch sampling (RBS) techniques (Schlecht and Affleck, 2014; Gregoire and Valentine, 2008). Between 5 and 10 live branches were selected from each sample tree by RBS, with the target number of branches set as an increasing function of tree dbh. Conditional RBS branch selection probabilities were set proportional to branch basal area. Selected live branches were separated into fuel time-lag classes based on diameter thresholds: diameter $\leqslant$0.635 cm (1 h fuels); 0.635 cm

Table 1
Table of symbols.

Symbol	Description
d	Outside-bark diameter at breast height (1.37 m; cm)
h	Total tree height (m)
l	Live crown length (m)
m_d	Dry mass of dead first-order branches (kg)
m_f	Dry mass of foliage (kg)
m_{l_1}	Dry mass of materials $\leqslant$ 0.635 cm in diameter in live branches (kg)
$m_{l_{10}}$	Dry mass of materials 0.635–2.54 cm in diameter in live branches (kg)
$m_{l_{100+}}$	Dry mass of materials >2.54 cm in diameter in live branches (kg)
m_l	Dry mass of live first-order branches ($m_{l_1} + m_{l_{10}} + m_{l_{100+}}$; kg)
m_c	Dry mass of the crown ($m_d + m_f + m_l$; kg)
m_w	dry mass of wood in the main stem from a 30 cm stump to a 5 cm top (kg)
m_b	Dry mass of bark in the main stem from a 30 cm stump to a 5 cm top (kg)
m_s	Dry mass of the main stem from a 30 cm stump to a 5 cm top ($m_w + m_b$; kg)
m_a	Abovestump dry mass of the tree based on a 30 cm stump ($m_c + m_s$; kg)
$c_{dh,i}$	Principal component i of ln d and ln h
$c_{dhl,i}$	Principal component i of ln d, ln h, and ln l
β_{ci}	Parameter of the expectation function of biomass component c
α_i	Parameter of the live branch disaggregation function
θ_{ci}	Parameter of the variance function of biomass component c