Estimating Aboveground Biomass for Broadleaf Woody Plants and Young Conifers in Sierra Nevada, California, Forests

Thomas W. McGinnis, Christine D. Shook, and Jon E. Keeley

ABSTRACT

Quantification of biomass is fundamental to a wide range of research and natural resource management goals. An accurate estimation of plant biomass is essential to predict potential fire behavior, calculate carbon sequestration for global climate change research, assess critical wildlife habitat, and so forth. Reliable allometric equations from simple field measurements are necessary for efficient evaluation of plant biomass. However, allometric equations are not available for many common woody plant taxa in the Sierra Nevada. In this report, we present more than 200 regression equations for the Sierra Nevada western slope that relate crown diameter, plant height, crown volume, stem diameter, and both crown diameter and height to the dry weight of foliage, branches, and entire aboveground biomass. Destructive sampling methods resulted in regression equations that accurately predict biomass from one or two simple, nondestructive field measurements. The tables presented here will allow researchers and natural resource managers to easily choose the best equations to fit their biomass assessment needs.

Keywords: biomass, regression, shrub, conifer, foliage

Biomass estimation is an essential part of many research programs because of its relevance in several fields and the fact that direct measurements of biomass are destructive and work-intensive. Land managers rely on allometric relationships between biomass and easily obtained plant dimensions, such as stem diameter, canopy diameter, and canopy height, to inventory and monitor natural resources. Developing allometric relationships between easily measured parameters and shrub biomass has been particularly important in ecological studies of productivity (e.g., Whittaker and Woodwell 1968), wildlife habitat (Marshall et al. 1990), and forest restoration (Hughes et al. 1987). Fire behavior specialists use biomass regressions to formulate fuel models that, when integrated with fuel moisture, weather, and topography, help to predict potential fire behavior. In part because of their multistem form and diverse branching patterns, shrubs and hardwood trees are difficult to predict. To varying degrees, many conifer species also have complex shrublike morphologies when they are young and relatively uniform stems and radially symmetrical branches at middle age, until eventually fire, herbivory, and pathogens result in complex morphologies.

The goal in developing biomass regressions is to accurately predict biomass from easily sampled plant measurements. For shrubs, stem diameter or basal area, crown diameter, crown area, plant height, crown volume, and other measurements have been used as independent variables in biomass regression equations (e.g., Gholz et al. 1979, Smith and Brand 1983, Ross and Walstad 1986). For conifers, stem diameter, stem area, and stem circumference have been widely used (e.g., Jenkins et al. 2004).

Several authors have published biomass regression equations for western North American species of broadleaf woody plants (Chojnacky 1984, Hughes et al. 1987, Vora 1988), conifers (Krumlik 1974, Fujimori et al. 1976), or both (Gholz et al. 1979, Ross and Walstad 1986). Means et al. (1996), Ter-Mikaelian and Korzukhin (1997), Smith and Brand (1983), and Jenkins et al. (2004) have compiled equations from several sources. Few of these studies provide equations that estimate biomass by branch size class, a useful variable for fire behavior models (Reinhardt et al. 2006).

In this article and on our web page (McGinnis and Keeley 2010), we present biomass regression equations for 20 common shrub and tree genera, plus several groups of related species from mid-elevation Sierra Nevada coniferous forests that experienced stand-replacing fires in the last 20 years. These equations relate crown diameter, plant height, crown volume, and stem diameter to dry weight of foliage, branches, and entire aboveground biomass. Although considerable research has been done by other scientists estimating the biomass of individual tree and shrub species, few studies have used regression equations to predict the biomass of the common woody plant species in western slope Sierra Nevada forests. Also, to our knowledge, we provide the first published regression equations that use crown diameter to predict biomass of *A. concolor*, *Calocedrus*

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This article uses metric units; the applicable conversion factors are: millimeter (mm): 1 mm = 0.039 in.; centimeters (cm): 1 cm = 0.39 in.

decurrens, *Pinus jeffreyi* and *Pinus lambertiana*, expanding the field collection methods available to scientists and managers who wish to measure conifer biomass in a nondestructive manner.

Materials and Methods

Study Areas

Study sites were located in the northern, central, and southern regions of the Sierra Nevada, on the western slope (Figure 1). All but one of 34 collection sites experienced a stand-replacing fire within the last 20 years (one site did not recently burn, but herbicide application resulted in <20 year-old shrubs). The three burned areas in this study, from north to south, were (a) the 2001 Star Fire area (39.1°N, 120.5°W, Tahoe and Eldorado National Forests), (b) the 1987 Stanislaus Complex (37.9°N, 120.0°W, Stanislaus National Forest), and (c) the 2002 McNally Fire area (36.1°N, 118.3°W, Sequoia National Forest). Collection sites were located in both untreated and postfire-treated areas. The US Forest Service prepared and maintained conifer plantations in many of these areas using a variety of postfire shrub removal treatments, including deep tilling (Stanislaus National Forest), scraping by hand and heavy equipment (all forests), prescribed burning (Stanislaus National Forest), and spraying herbicides (Stanislaus and Eldorado National Forests).

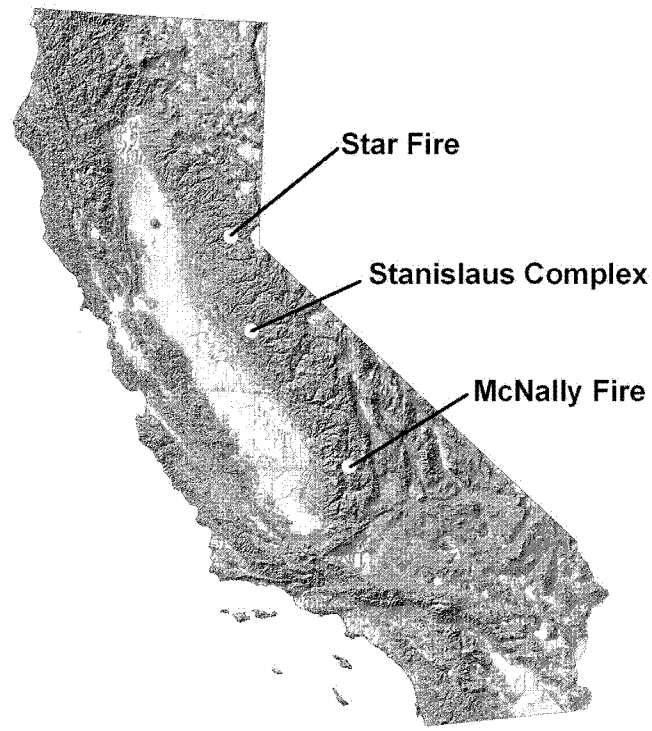

Figure 1. Map of the biomass collection sites in California's Sierra Nevada.

Shrub and Conifer Biomass

Common shrubs and hardwood trees were collected from the three Sierra Nevada regions in the montane coniferous zone. These broadleaf plants were collected in summer-autumn 2007, when leaves were mostly mature. Specimens were <3 years old to approximately 20 years old. Conifer seedlings and saplings were collected in early summer 2008, when foliage was not fully exerted. Conifers up to 1.4 m tall were collected only from plantations on the Eldorado National Forest (*A. concolor*, 0.17–1.19 m, *C. decurrens*, 0.35–0.85 m, *P. jeffreyi*, 0.14–1.02 m, and *P. lambertiana*, 0.14–1.44 m). Shrub and hardwood tree collection sites were randomly selected from both conifer plantations and untreated stands delineated in a related study (McGinnis et al. 2010). The shrubs and hardwood trees in these sites represent the wide range of morphologies and sizes throughout the Sierra Nevada western side, growing in isolation and in densely populated stands. Within each site, a single specimen of each common species (known from previous sampling in the area) was randomly selected by pivoting a 100-m tape measure in a random direction, then locating the common woody plant nearest a random number on the tape measure. To ensure a range of plant sizes, we randomly selected a new sample if we already had representatives from the size first selected. For broadleaf plants, this sampling scheme resulted in more specimens of wide-ranging species, as they occurred in more plots than less ubiquitous ones. Also for broadleaf plants, random sampling ensured the selection of plants that were both impeded and unimpeded by surrounding vegetation and obstacles, so that the our biomass predictions would be applicable anywhere in the study area. However, for conifers, which were sampled only in plantations with adequate spacing and few shrubs, these equations only represent plantation conifers with little competition.

Once the plant had been identified by species, the geometric shape of the plant was recorded, and crown volume was estimated from a common geometric formula (sphere, circular frustum, etc.) along with measurements (excluding unusually long branches) of total plant height, maximum width, and width perpendicular to the maximum. Crown diameter (mean canopy breadth) was the average of the maximum width and the width perpendicular to the maximum, as per Ross and Walstad (1986). For conifers, stem diameter was also measured at the soil surface. Plants were cut at the soil surface and placed into bags. All aboveground biomass was collected from small plants, but only a fraction of large specimens was collected, based on visual estimation. This fraction was recorded and the biomass of the total plant was later estimated from the fraction collected.

Specimens were dissected into live and dead leaves and branches, and branches were further subdivided by size class (<0.64, 0.64–2.53, and 2.54–7.6 cm), which, if dry, would represent 1-, 10-, and 100-hour fuel classes used in fire behavior models (as per Brown 1974). Foliage plus a fraction of the finest live branches are considered to be "available live fuel" (e.g., Reinhardt et al. 2006). Only foliage, <0.64 cm branches, and total aboveground biomass are reported here, as these are the most widely used values for fire behavior modeling and carbon load calculations; additional size classes are reported on our web page (McGinnis and Keeley 2010). Flowers and fruits were excluded to ignore differences in phenology. Subsamples were randomly selected, weighed, dried in an 80°C oven, and reweighed to determine moisture content and oven-dry weight of the entire sample.

Statistical Analysis

We used Systat (version 11) statistical software to compute regression equations for natural-log-transformed independent and dependant variables. Regression equations were developed for each of the following independent variables: average crown diameter, plant

Table 1. Regression equations for aboveground biomass of broadleaf shrubs and trees in northern (N), central (C), and southern (S) Sierra Nevada western slope collection sites.

Species, Site(s), and Biomass type	N	Crown diameter (cm) a	b	P value	R^2	Standard error of estimate	CF	Plant height (cm) a	b	P value	R^2	Standard error of estimate	CF	Crown volume (m^3) a	b	P value	R^2	Standard error of estimate	CF	Crown diameter and plant height (cm) a	b_1	b_2	P value	Adj. R^2	Standard error of estimate	CF
All broadleaf species listed below plus those listed in the table heading (collection sites: NCS)																										
<0.64 cm live	147	−4.254	2.121	<0.001	0.869	0.67	1.25	−1.597	1.557	<0.001	0.44	1.37	2.56	6.362	0.739	<0.001	0.87	0.66	1.25	−4.250	2.124	−0.004	<0.001	0.87	0.67	1.25
Live foliage	143	−4.168	1.889	<0.001	0.685	1.03	1.69	−2.076	1.461	<0.001	0.40	1.42	2.72	5.297	0.662	<0.001	0.70	1.00	1.65	−4.363	1.754	0.193	<0.001	0.68	1.02	1.69
Total biomass	147	−4.305	2.312	<0.001	0.868	0.73	1.30	−2.062	1.863	<0.001	0.53	1.37	2.55	7.278	0.812	<0.001	0.88	0.69	1.27	−4.658	2.079	0.336	<0.001	0.88	0.71	1.28
Arctostaphylos patula (collection sites: NS)																										
<0.64 cm live	18	−3.844	2.042	<0.001	0.930	0.32	1.05	−0.966	1.368	0.001	0.48	0.87	1.46	6.147	0.644	<0.001	0.91	0.37	1.07	−3.949	1.937	0.143	<0.001	0.92	0.33	1.05
Live foliage	18	−6.008	2.611	<0.001	0.942	0.37	1.07	−2.208	1.714	0.002	0.47	1.12	1.88	6.753	0.819	<0.001	0.91	0.47	1.12	−6.095	2.524	0.118	<0.001	0.94	0.38	1.07
Total biomass	18	−4.218	2.383	<0.001	0.950	0.31	1.05	−1.002	1.638	0.001	0.52	0.97	1.60	7.439	0.750	<0.001	0.92	0.39	1.08	−4.396	2.204	0.224	<0.001	0.95	0.30	1.05
Arctostaphylos viscida (collection sites: C)																										
<0.64 cm live	7	−4.250	2.125	0.001	0.921	0.68	1.26	−5.706	2.374	0.002	0.86	0.89	1.48	6.188	0.741	<0.001	0.95	0.55	1.16	−4.073	2.305	−0.214	0.006	0.88	0.76	1.33
Live foliage	7	−3.080	1.914	0.003	0.854	0.86	1.44	−4.093	2.069	0.012	0.75	1.12	1.88	6.331	0.671	0.001	0.89	0.75	1.32	−1.832	3.192	−1.514	0.015	0.81	0.89	1.48
Total biomass	7	−4.315	2.484	<0.001	0.944	0.66	1.24	−5.584	2.697	0.004	0.84	1.12	1.87	7.868	0.858	<0.001	0.95	0.60	1.20	−2.892	3.941	−1.726	0.001	0.94	0.60	1.20
Ceanothus cordulatus (collection sites: NS)																										
<0.64 cm live	19	−4.912	2.295	<0.001	0.883	0.56	1.17	−4.506	2.611	<0.001	0.63	1.00	1.65	6.644	0.812	<0.001	0.89	0.55	1.16	−5.909	1.903	0.715	<0.001	0.89	0.52	1.15
Live foliage	18	−7.693	2.579	<0.001	0.874	0.67	1.25	−6.401	2.728	0.001	0.54	1.29	2.28	5.292	0.919	<0.001	0.89	0.64	1.23	−8.228	2.370	0.382	<0.001	0.86	0.68	1.26
Total biomass	19	−6.025	2.653	<0.001	0.902	0.59	1.19	−5.557	3.019	<0.001	0.64	1.12	1.88	7.334	0.939	<0.001	0.91	0.57	1.18	−7.179	2.199	0.828	<0.001	0.91	0.54	1.15
Ceanothus fresnensis and *Ceanothus pinetorum* (collection sites: NCS)																										
<0.64 cm live	8	−3.406	2.016	0.002	0.821	0.53	1.15	0.780	1.212	0.040	0.53	0.85	1.43	6.591	0.606	0.005	0.75	0.62	1.21	−3.416	2.026	−0.009	0.014	0.75	0.58	1.18
Live foliage	8	−4.539	2.115	0.004	0.777	0.63	1.22	−1.039	1.540	0.006	0.74	0.69	1.26	6.051	0.671	0.003	0.79	0.61	1.20	−3.717	1.293	0.761	0.010	0.78	0.59	1.19
Total biomass	8	−3.326	2.120	0.001	0.846	0.50	1.13	0.803	1.356	0.020	0.62	0.79	1.37	7.233	0.654	0.002	0.82	0.55	1.16	−3.083	1.877	0.225	0.008	0.79	0.54	1.16
Ceanothus integerrimus (collection sites: NC)																										
<0.64 cm live	10	−2.194	1.720	0.001	0.747	0.73	1.31	−0.840	1.471	0.024	0.49	1.03	1.71	6.365	0.618	<0.001	0.81	0.63	1.22	−2.282	1.659	0.081	0.008	0.68	0.78	1.35
Live foliage	10	−4.541	1.849	0.003	0.690	0.90	1.50	−4.185	1.812	0.009	0.60	1.03	1.70	4.661	0.670	0.001	0.76	0.79	1.37	−5.323	1.309	0.715	0.011	0.65	0.91	1.51
Total biomass	10	−3.000	2.051	<0.001	0.823	0.69	1.27	−2.509	1.989	0.003	0.70	0.91	1.51	7.200	0.725	<0.001	0.87	0.60	1.20	−3.807	1.494	0.738	0.001	0.82	0.66	1.25
Chrysolepis sempervirens (collection sites: NS)																										
<0.64 cm live	6	−3.657	1.963	<0.001	0.972	0.23	1.03	−3.940	2.146	0.047	0.67	0.79	1.36	6.470	0.746	0.001	0.96	0.28	1.04	−3.747	1.918	0.072	0.005	0.95	0.26	1.03
Live foliage	5	−2.918	1.811	0.100	0.648	0.46	1.11	0.047	1.147	0.481	0.18	0.71	1.28	6.394	0.673	0.062	0.74	0.40	1.08	−5.774	1.713	0.860	0.253	0.49	0.48	1.12
Total biomass	6	−4.965	2.533	<0.001	0.966	0.33	1.05	−6.019	2.960	0.024	0.76	0.87	1.46	8.099	0.961	0.001	0.95	0.41	1.09	−5.807	2.112	0.677	0.003	0.97	0.29	1.04
Chrysothamnus nauseosus and *Chrysothamnus parryi* (collection sites: CS)																										
<0.64 cm live	8	−3.502	1.954	<0.001	0.905	0.63	1.22	−7.069	2.681	0.010	0.70	1.12	1.88	6.350	0.721	<0.001	0.90	0.65	1.24	−4.497	1.705	0.467	0.002	0.88	0.67	1.25
Live foliage	8	−3.069	1.637	0.002	0.827	0.75	1.32	−6.404	2.327	0.011	0.69	1.01	1.66	5.207	0.612	0.001	0.84	0.71	1.29	−4.459	1.289	0.653	0.010	0.78	0.78	1.35
Total biomass	8	−3.871	2.263	0.001	0.839	0.99	1.63	−8.690	3.265	0.008	0.72	1.31	2.36	7.563	0.844	0.001	0.85	0.95	1.57	−6.128	1.698	1.060	0.007	0.81	1.00	1.65
Prunus emarginata (collection sites: N)																										
<0.64 cm live	6	−3.086	1.780	0.002	0.925	0.36	1.07	−5.538	2.308	0.110	0.51	0.92	1.53	5.693	0.594	0.006	0.88	0.46	1.11	−1.018	2.190	−0.860	0.012	0.91	0.35	1.06
Live foliage	5	−10.083	3.006	0.035	0.817	1.17	1.99	−20.045	5.162	0.089	0.67	1.57	3.43	4.810	1.082	0.016	0.89	0.91	1.52	−11.353	2.760	0.525	0.181	0.64	1.43	2.78
Total biomass	6	−3.370	1.970	0.003	0.913	0.44	1.10	−6.683	2.691	0.086	0.56	0.98	1.61	6.375	0.672	0.003	0.91	0.45	1.11	−2.176	2.215	−0.512	0.023	0.87	0.48	1.12
Quercus chrysolepis, Quercus kelloggii, Quercus vaccinifolia, and *Quercus wislizenii* (collection sites: NCS)																										
<0.64 cm live	11	−3.896	1.995	<0.001	0.847	0.82	1.40	0.421	1.059	0.116	0.25	1.81	5.15	6.008	0.688	<0.001	0.83	0.87	1.46	−2.928	2.693	−0.908	<0.001	0.91	0.60	1.19
Live foliage	11	−4.035	1.960	<0.001	0.862	0.76	1.33	−0.317	1.154	0.073	0.31	1.69	4.14	5.703	0.684	<0.001	0.86	0.76	1.33	−3.360	2.447	−0.633	<0.001	0.88	0.67	1.25
Total biomass	11	−3.669	2.216	<0.001	0.946	0.51	1.14	−0.238	1.472	0.026	0.44	1.65	3.88	7.340	0.774	<0.001	0.95	0.51	1.14	−3.313	2.473	−0.334	<0.001	0.95	0.49	1.13
Q. kelloggii (collection sites: NC)																										
<0.64 cm live	6	−3.537	1.829	0.001	0.962	0.29	1.04	−1.608	1.342	0.036	0.71	0.79	1.37	5.508	0.575	0.004	0.90	0.47	1.12	−3.593	2.454	−0.583	0.002	0.97	0.22	1.02
Live foliage	6	−5.602	2.184	<0.001	0.988	0.19	1.02	−3.662	1.677	0.017	0.80	0.78	1.36	5.209	0.697	0.001	0.95	0.38	1.08	−5.623	2.425	−0.225	0.001	0.98	0.20	1.02
Total biomass	6	−3.393	2.109	<0.001	0.984	0.21	1.02	−1.936	1.705	0.006	0.88	0.58	1.18	7.059	0.685	<0.001	0.98	0.23	1.03	−3.362	1.763	0.322	0.001	0.98	0.20	1.02
Ribes (currant and gooseberry) (collection sites: NCS)																										
<0.64 cm live	18	−4.318	2.094	<0.001	0.847	0.76	1.33	−7.644	3.015	<0.001	0.68	1.10	1.83	6.291	0.766	<0.001	0.84	0.78	1.35	−6.079	1.640	0.923	<0.001	0.85	0.72	1.29
Live foliage	17	−6.576	2.293	<0.001	0.836	0.82	1.40	−9.646	3.187	<0.001	0.72	1.08	1.79	5.013	0.822	<0.001	0.82	0.86	1.45	−8.476	1.672	1.140	<0.001	0.85	0.77	1.34
Total biomass	18	−4.859	2.344	<0.001	0.844	0.86	1.44	−8.709	3.409	<0.001	0.69	1.21	2.08	7.023	0.858	<0.001	0.84	0.87	1.46	−6.998	1.794	1.121	<0.001	0.86	0.80	1.38
Symphoricarpos sp. (collection sites: NS)																										
<0.64 cm live	11	−6.141	2.548	0.018	0.480	0.90	1.49	−0.482	1.445	0.047	0.37	0.99	1.63	7.132	0.947	0.002	0.68	0.70	1.28	−6.593	1.931	0.883	0.028	0.49	0.84	1.43
Live foliage	11	−8.378	2.648	0.043	0.382	1.14	1.91	−1.586	1.235	0.168	0.20	1.30	2.31	4.952	0.820	0.044	0.38	1.14	1.92	−8.677	2.241	0.583	0.115	0.27	1.17	1.99
Total biomass	11	−6.840	2.784	0.015	0.497	0.95	1.57	−0.442	1.515	0.054	0.35	1.08	1.78	7.550	0.995	0.003	0.65	0.79	1.36	−7.294	2.165	0.885	0.027	0.49	0.90	1.50

The equation form for a single independent variable is $Y = \exp[a + b\ln(x)]$, where x = independent variable (crown diameter, plant height, or crown volume). The equation form for crown diameter and plant height together is $Y = \exp[a + b_1\ln(\text{crown diameter}) + b_2\ln(\text{height})]$. Crown diameter for these equations was defined as 0.5 * (maximum crown width + perpendicular crown width), but for efficiency in using these equations in the field, only one average diameter measurement is needed. All results are based on natural-log-transformed independent and dependent values. Predicted biomass should be multiplied by the correction factor (CF) to correct for log bias, as per Sprugel (1983). All broadleaf species (first set of equations) includes all the species listed in the first column, plus the following: *Ceanothus cuneatus, Chamaebatia foliolosa, Eriodictyon californicum, Heteromeles arbutifolia, Nama lobbii, Purshia tridentata,* and *Toxicodendron diversilobum.*

height, crown volume, and both crown diameter and plant height. An additional independent variable for conifers was stem diameter at the soil surface. Dependent variables included live foliage; dead foliage; all foliage; live branches <0.64, 0.64–2.53, and 2.54–7.6 cm; dead branches for these size classes; and total biomass. Specimens that did not have a biomass category (e.g., larger branches) were not included in the regression equations (zeros were excluded). The following simple linear regression formula was used to predict biomass (Y), in grams, for individual species and multiple-species groups:

$$Y = \exp[a + b * \ln(x)], \quad (1)$$

where x is the independent variable.

The multiple linear regression formula (where diameter and height were used to predict biomass) was in the following form:

$$Y = \exp[a + b_1 * \ln(\text{crown diameter}) + b_2 * \ln(\text{height})] \quad (2)$$

Results

More than 400 regression equations were developed to estimate oven-dry weights of foliage and branches from 20 common broadleaf and coniferous woody Sierra Nevada plant species, plus additional groups of species. Tables 1 and 3 include 231 of these equations that would be most useful for fire behavior fuel modeling and carbon load assessments. Tables 2 and 4 list the range of plant sizes sampled and equations for calculating lower and upper biomass

Table 2. Plant sizes used for the regression equations (crown diameter, plant height, and crown volume) and data needed to calculate lower and upper limits of predicted biomass at 80% confidence, as per Neter et al. (1990).

Species	Site(s)	Biomass type	N	Crown diameter, min-max	Plant height, min-max	Crown volume, min-max (m^3)	MSE_d = Crown diameter mean square error	MSE_h = Plant height mean square error	MSE_V = Crown volume mean square error	MSE_{dh} = Crown diameter and plant height mean square error	s00 = Var(a) for multiple regression	s01 = Cov(a, b_1)	s11 = Var(b_1)	s02 = Cov(a, b_2)	s12 = Cov(b_1, b_2)	s22 = Var(b_2)	Simple regression t critical value for 80% confidence intervals	Multiple regression t critical value for 80% confidence intervals	SSX = $\Sigma(X_i - X_{mean})^2$	Mean ln Diameter	Mean ln Height	Mean ln Vol
All broadleaf species listed below plus those listed in the table heading	NCS	<0.64 cm live	147	13–348	6–410	0.001–17	0.443	1.880	0.441	0.446	0.095	−0.012	0.010	−0.011	−0.007	0.010	1.287	1.287	94.285	4.127	3.918	−2.516
		Live foliage	143				1.050	2.002	1.004	1.046	0.231	−0.031	0.024	−0.025	−0.017	0.024	1.288	1.288	90.045	4.145	3.928	−2.468
		Total biomass	147				0.528	1.871	0.474	0.498	0.106	−0.013	0.011	−0.012	−0.008	0.011	1.287	1.287	94.285	4.127	3.918	−2.516
A. patula	NS	<0.64 cm live	18	19–119	8–79	0.002–0.4	0.104	12.201	0.139	0.106	0.305	−0.058	0.038	−0.024	−0.024	0.032	1.337	1.341	5.265	3.731	3.465	−3.689
		Live foliage	18				0.138	20.168	0.218	0.144	0.411	−0.078	0.051	−0.032	−0.032	0.044	1.337	1.341	5.265	3.731	3.465	−3.689
		Total biomass	18				0.098	0.944	0.151	0.092	0.263	−0.050	0.032	−0.020	−0.020	0.028	1.337	1.341	5.265	3.731	3.465	−3.689
A. viscida	C	<0.64 cm live	7	16–179	19–160	0.002–2	0.458	0.785	0.299	0.570	3.400	1.306	1.841	−2.020	−2.066	2.449	1.476	1.533	5.891	4.132	4.312	−2.237
		Live foliage	7				0.736	1.260	0.561	0.786	4.687	1.801	2.541	−2.785	−2.851	3.378	1.476	1.533	5.891	4.132	4.312	−2.237
		Total biomass	7				0.430	6.259	0.356	0.364	2.167	0.833	1.175	−1.288	−1.318	1.563	1.476	1.533	5.891	4.132	4.312	−2.237
C. cordulatus	NS	<0.64 cm live	19	28–212	25–145	0.01–3	0.314	16.968	0.297	0.272	1.071	−0.058	0.078	−0.198	−0.078	0.142	1.333	1.337	7.679	4.688	3.965	−0.982
		Live foliage	18				0.452	26.415	0.409	0.463	1.855	−0.103	0.134	−0.338	−0.132	0.241	1.337	1.341	7.563	4.707	3.976	−0.920
		Total biomass	19				0.347	1.260	0.328	0.286	1.124	−0.061	0.082	−0.208	−0.082	0.149	1.333	1.337	7.679	4.688	3.965	−0.982
C. fresnensis, and *C. pinetorum*	NCS	<0.64 cm live	8	26–117	6–57	0.003–0.4	0.276	0.721	0.383	0.331	3.301	−1.052	0.508	0.307	−0.307	0.284	1.440	1.476	1.864	4.063	3.305	−2.979
		Live foliage	8				0.400	0.469	0.371	0.345	3.441	−1.095	0.529	0.320	−0.319	0.296	1.440	1.476	1.864	4.063	3.305	−2.979
		Total biomass	8				0.253	0.626	0.304	0.292	2.917	−0.929	0.449	0.271	−0.271	0.251	1.440	1.476	1.864	4.063	3.305	−2.979
C. integerrimus	NC	<0.64 cm live	10	22–164	35–246	0.004–5	0.532	8.551	0.399	0.607	3.948	−0.338	0.388	−0.473	−0.325	0.432	1.397	1.415	4.250	4.857	4.760	−0.333
		Live foliage	10				0.816	8.491	0.625	0.830	5.396	−0.462	0.531	−0.648	−0.445	0.590	1.397	1.415	4.250	4.857	4.760	−0.333
		Total biomass	10				0.482	0.822	0.365	0.441	2.866	−0.245	0.282	−0.343	−0.236	0.314	1.397	1.415	4.250	4.857	4.760	−0.333
C. sempervirens	NS	<0.64 cm live	6	15–79	16–59	0.002–0.1	0.052	2.479	0.081	0.069	0.835	0.011	0.111	−0.240	−0.120	0.193	1.533	1.638	1.891	3.803	3.611	−3.569
		Live foliage	5				0.214	1.502	0.158	0.232	21.10	−2.226	0.654	−3.203	−0.110	0.964	1.638	1.886	0.361	4.029	3.779	−2.995
		Total biomass	6				0.106	0.754	0.164	0.086	1.051	0.014	0.140	−0.302	−0.151	0.243	1.533	1.638	1.891	3.803	3.611	−3.569
C. nauseosus and *C. parryi*	CS	<0.64 cm live	8	14–280	17–77	0.002–6	0.398	1.262	0.422	0.445	3.960	0.364	0.241	−1.253	−0.313	0.588	1.440	1.476	5.973	4.076	4.301	−2.619
		Live foliage	8				0.559	1.016	0.506	0.607	5.406	0.498	0.329	−1.710	−0.428	0.803	1.440	1.476	5.973	4.076	4.301	−2.619
		Total biomass	8				0.976	1.719	0.898	1.001	8.916	0.821	0.543	−2.822	−0.706	1.325	1.440	1.476	5.973	4.076	4.301	−2.619
P. emarginata	N	<0.64 cm live	6	25–174	58–160	0.01–3	0.132	0.853	0.213	0.125	4.402	0.401	0.197	−1.393	−0.285	0.598	1.533	1.638	2.043	4.313	4.389	−1.855
		Live foliage	5				1.376	2.465	0.835	2.047	118.4	14.889	4.731	−40.987	−7.950	16.941	1.638	1.886	2.040	4.323	4.448	−1.752
		Total biomass	6				0.189	3.810	0.201	0.234	8.271	0.752	0.370	−2.616	−0.535	1.121	1.533	1.638	2.043	4.313	4.389	−1.855
Q. chrysolepis, *Q. kelloggii*, *Q. vaccinifolia*, and *Q. wislizenii*	NCS	<0.64 cm live	11	15–348	22–410	0.003–11	0.670	3.277	0.763	0.355	1.036	−0.120	0.097	−0.098	−0.071	0.092	1.383	1.397	8.374	4.608	4.607	−1.030
		Live foliage	11				0.570	2.842	0.575	0.448	1.309	−0.152	0.122	−0.123	−0.089	0.116	1.383	1.397	8.374	4.608	4.607	−1.030
		Total biomass	11				0.259	2.708	0.259	0.238	0.694	−0.080	0.065	−0.065	−0.047	0.062	1.383	1.397	8.374	4.608	4.607	−1.030
Q. kelloggii	NC	<0.64 cm live	6	55–308	52–410	0.1–8	0.082	2.524	0.218	0.049	0.425	−0.100	0.123	0.009	−0.097	0.090	1.533	1.638	2.483	4.615	5.852	−1.052
		Live foliage	6				0.036	2.439	0.145	0.039	0.343	−0.080	0.099	0.007	−0.078	0.073	1.533	1.638	2.483	4.615	5.852	−1.052
		Total biomass	6				0.044	0.337	0.053	0.040	0.353	−0.083	0.102	0.007	−0.080	0.075	1.533	1.638	2.483	4.615	5.852	−1.052
Ribes (currant and gooseberry)	NCS	<0.64 cm live	18	13–318	20–165	0.001–8	0.573	1.210	0.604	0.517	1.866	0.114	0.120	−0.595	−0.153	0.311	1.337	1.341	11.547	3.962	3.854	−3.020
		Live foliage	17				0.678	1.164	0.740	0.591	2.132	0.126	0.180	−0.673	−0.220	0.403	1.341	1.345	9.881	4.036	3.867	−2.839
		Total biomass	18				0.731	1.467	0.757	0.640	2.310	0.142	0.148	−0.736	−0.189	0.386	1.337	1.341	11.547	3.962	3.854	−3.020
Symphoricarpos sp.	NS	<0.64 cm live	11	32–101	13–60	0.01–0.3	0.803	0.972	0.489	0.711	12.110	−2.744	0.867	−0.184	−0.252	0.361	1.383	1.397	1.029	4.158	3.417	−2.828
		Live foliage	11				1.295	1.678	1.305	1.373	23.387	−5.300	1.674	−0.355	−0.487	0.697	1.383	1.397	1.029	4.158	3.417	−2.828
		Total biomass	11				0.897	1.153	0.617	0.817	13.905	−3.152	0.996	−0.211	−0.290	0.415	1.383	1.397	1.029	4.158	3.417	−2.828

The lower and upper limits are determined as exp(XB − tSE) and exp(XB + tSE), respectively. For the simple regression, XB = $a + bx$, with x = ln(crown diameter in cm), ln(plant height in cm), or ln(crown volume in m^3), depending on the regression predictor, and SE = $\sqrt{\{MSE[1 + 1/N + (x - X_{mean})^2/SSX]\}}$. For the multiple regression using both crown diameter and height, XB = $a + b_1$ln(diameter) + $b_2$ln(height), and SE = $\sqrt{\{MSE + s00 + s11 \ln(diameter)^2 + s22 \ln(height)^2 + 2[s01 \ln(diameter) + s02 \ln(height) + s12 \ln(diameter)\ln(height)]\}}$.

Table 3. Regression equations for aboveground biomass of conifers in the northern Sierra Nevada western slope collection site.

Species	Biomass type	N	Crown diameter (cm) a	b	P value	R^2	Standard error of estimate	CF	Tree height (cm) a	b	P value	R^2	Standard error of estimate	CF	Crown volume (m^3) a	b	P value	R^2	Standard error of estimate	CF	Stem diameter at soil surface (cm) a	b	P value	R^2	Standard error of estimate	CF	Crown diameter and tree height (cm) a	b_1	b_2	P value	Adj. R^2	Standard error of estimate	CF
A. concolor, *C. decurrens*, *P. jeffreyi*, and *P. lamberiana*	<0.64 cm live	31	−4.660	2.053	<0.001	0.92	0.41	1.09	−5.426	2.032	<0.001	0.86	0.53	1.15	5.241	0.694	<0.001	0.82	0.60	1.20	1.916	1.688	<0.001	0.80	0.63	1.22	−5.143	1.486	0.626	<0.001	0.92	0.38	1.08
	Live foliage	31	−4.516	2.350	<0.001	0.94	0.41	1.09	−5.231	2.287	<0.001	0.85	0.62	1.21	6.88	0.814	<0.001	0.88	0.56	1.17	2.963	2.005	<0.001	0.88	0.55	1.17	−4.859	1.947	0.445	<0.001	0.94	0.40	1.08
	Total biomass	31	−4.545	2.513	<0.001	0.94	0.42	1.09	−5.403	2.468	<0.001	0.87	0.62	1.21	7.637	0.869	<0.001	0.88	0.60	1.20	3.437	2.167	<0.001	0.91	0.53	1.15	−5.032	1.942	0.631	<0.001	0.95	0.39	1.08
A. concolor	<0.64 cm live	8	−5.689	2.327	<0.001	0.97	0.25	1.03	−5.142	2.058	<0.001	0.92	0.42	1.09	5.938	0.842	<0.001	0.97	0.26	1.03	2.324	1.844	0.005	0.76	0.73	1.31	−5.707	2.567	−0.22	<0.001	0.96	0.27	1.04
	Live foliage	8	−5.173	2.471	<0.001	0.93	0.44	1.10	−4.314	2.111	0.002	0.82	0.69	1.27	7.209	0.903	<0.001	0.94	0.39	1.08	3.326	2.022	0.004	0.77	0.78	1.35	−5.326	4.602	−1.98	<0.001	0.94	0.37	1.07
	Total biomass	8	−5.077	2.575	<0.001	0.95	0.39	1.08	−4.263	2.222	0.001	0.86	0.64	1.23	7.813	0.938	<0.001	0.96	0.35	1.06	3.782	2.104	0.003	0.79	0.78	1.35	−5.198	4.25	−1.55	<0.001	0.95	0.35	1.06
C. decurrens	<0.64 cm live	7	−4.521	2.017	0.002	0.88	0.34	1.06	−4.971	1.864	0.15	0.37	0.79	1.36	4.042	0.432	0.126	0.40	0.76	1.34	1.574	1.479	0.055	0.55	0.66	1.24	−3.955	2.137	−0.25	0.014	0.82	0.38	1.07
	Live foliage	7	−4.461	2.426	<0.001	0.95	0.27	1.04	−4.896	2.215	0.137	0.39	0.90	1.50	5.977	0.556	0.078	0.49	0.81	1.39	2.762	1.977	0.013	0.74	0.59	1.19	−3.661	2.595	−0.35	0.002	0.93	0.28	1.04
	Total biomass	7	−3.907	2.402	<0.001	0.94	0.28	1.04	−4.138	2.142	0.151	0.36	0.91	1.51	6.37	0.536	0.092	0.46	0.83	1.41	3.201	2.038	0.007	0.79	0.52	1.14	−2.894	2.615	−0.44	0.003	0.92	0.29	1.04
P. jeffreyi	<0.64 cm live	8	−4.780	2.007	<0.001	0.93	0.48	1.12	−6.991	2.349	<0.001	0.91	0.52	1.14	4.805	0.627	0.003	0.80	0.78	1.35	1.540	1.748	<0.001	0.97	0.28	1.04	−5.361	1.528	0.573	0.001	0.90	0.52	1.14
	Live foliage	8	−5.523	2.561	<0.001	0.97	0.39	1.08	−8.395	3.009	<0.001	0.96	0.43	1.09	6.756	0.819	0.001	0.88	0.76	1.33	2.587	2.186	<0.001	0.98	0.33	1.05	−6.674	1.614	1.133	<0.001	0.96	0.39	1.08
	Total biomass	8	−5.548	2.745	<0.001	0.97	0.40	1.08	−8.588	3.216	<0.001	0.96	0.43	1.09	7.598	0.872	0.001	0.87	0.85	1.43	3.138	2.350	<0.001	0.99	0.28	1.04	−6.47	1.986	0.909	<0.001	0.96	0.42	1.09
P. lamberiana	<0.64 cm live	8	−3.373	1.819	<0.001	0.95	0.27	1.04	−6.212	2.197	<0.001	0.97	0.22	1.02	5.841	0.81	<0.001	0.96	0.24	1.03	1.788	2.081	<0.001	0.92	0.36	1.07	−5.277	0.696	1.389	<0.001	0.97	0.21	1.02
	Live foliage	8	−3.181	2.048	<0.001	0.96	0.28	1.04	−6.317	2.46	<0.001	0.97	0.26	1.03	7.19	0.912	<0.001	0.97	0.22	1.03	2.615	2.353	<0.001	0.93	0.36	1.07	−5.037	0.953	1.354	<0.001	0.97	0.22	1.02
	Total biomass	8	−2.708	2.098	<0.001	0.96	0.30	1.05	−6.04	2.546	<0.001	0.98	0.20	1.02	7.923	0.937	<0.001	0.97	0.24	1.03	3.200	2.440	<0.001	0.95	0.32	1.05	−5.183	0.638	1.806	<0.001	0.98	0.19	1.02

The equation form for a single independent variable is $Y = \exp[a + b\ln(x)]$, where x = independent variable (crown diameter, tree height, crown volume, or stem diameter at soil surface). The equation form for crown diameter and tree height together is $Y = \exp[a + b_1\ln(\text{crown diameter}) + b_2\ln(\text{height})]$. Crown diameter for these equations was defined as 0.5 * (maximum crown width + perpendicular crown width), but for efficiency in using these equations in the field, only one average diameter measurement is needed. All results are based on natural-log-transformed independent and dependent values. Predicted biomass should be multiplied by the correction factor (CF) to correct for log bias, as per Sprugel (1983).

limits at 80% confidence. The entire set of equations and biomass predictions with lower and upper limits is available on our web page (McGinnis and Keeley 2010).

Mean R^2 values for broadleaf taxa were 0.85–0.87 for crown diameter, volume, and crown diameter and height together. In contrast, height was the poorest predictor of biomass for broadleaf taxa, with a mean R^2 of 0.62. R^2 values were higher for conifers, with mean values of 0.93 for crown diameter and diameter and height together, 0.80 for height, 0.81 for volume, and 0.84 for stem diameter. More than half of the equations were highly significant (P = 0.001 or lower, as shown in the tables).

Discussion

Regression equations presented here and on our web page (McGinnis and Keeley 2010) can be used to calculate the total biomass and many individual components (e.g., foliage, fine braches, medium branches, total aboveground biomass) of common Sierra Nevada woody plant species. With the choice of generic equations for conifers and broadleaf woody plants, various multispecies groupings, single species from a broad area, and single species from a specific location, users can select the equations that most closely calculate biomass of the plants and areas of interest.

Regression equations using crown diameter, volume, and both crown diameter and height as predictors of broadleaf-woody plant biomass exhibited the best fit models. However, as others have indicated, volume is a labor-intensive field measurement; therefore, crown diameter or crown diameter and height together are preferable for efficiency when hundreds of field measurements are to be collected. Stem diameter is the most common independent variable in conifer equations (e.g., Jenkins et al. 2004, Tinker et al. 2010); however, crown diameter is just as easily obtained, and in our equations it resulted in better fit for the plantation seedlings and saplings. Multiple linear regressions with crown diameter and height also resulted in excellent fit.

We compared our equations with other published equations and found that for conifer foliage biomass, our equations for small trees supplement commonly used equations from larger trees collected in Oregon (used in Gholz et al. 1979, Means et al. 1996 and Jenkins et al. 2004). Our equations, with the independent variable of stem diameter at soil surface, resulted in approximately the same biomass predictions as the equations from Oregon specimens using dbh as the independent variable; for example, our estimates for *P. jeffreyi* foliage fell between values from two equations for *Pinus ponderosa* in Oregon (Fig. 2). These results indicate that the equations from Oregon are good predictors of these taxa in the Sierra Nevada and should be used for predictions from dbh, whereas our equations would be applicable to seedlings and saplings shorter than breast height. Here we assume that the relationship between stem diameter at soil surface and foliar biomass of small conifers is approximately the same as the relationship between dbh and foliar biomass of large conifers. In addition to adding new ways of measuring small trees for determining biomass, this study also adds a common western tree species (*C. decurrens*) and includes additional biomass categories used in fire behavior modeling.

We also compared our total aboveground biomass predictions with predictions from Oregon (Ross and Walstad 1986) for six shrub taxa and using crown diameter and crown volume as independent variables (Fig. 3). Using crown diameter as the independent variable (Fig. 3a), four of the six taxa in our study had predictions

Table 4. Plant sizes used for the regression equations (crown diameter, tree height, crown volume, and stem diameter) and data needed to calculate lower and upper limits of predicted biomass at 80% confidence, as per Neter et al. (1990).

Species	Biomass type	N	Crown diameter, min-max	Tree height, min-max	Crown volume, min-max (m^3)	Stem diameter, min-max (cm)	MSE_d = Crown diameter mean square error	MSE_h = Tree height mean square error	MSE_v = Crown volume mean square error	MSE_s = Stem diameter mean square error	MSE_{dh} = Crown diameter and tree height mean square error	s00 = Var(a) for multiple regression	s01 = Cov(a, b_1)	s11 = Var(b_1)	s02 = Cov(a, b_2)	s12 = Cov(b_1, b_2)	s22 = Var(b_2)	Simple regression t critical value for 80% confidence intervals	Multiple regression t critical value for 80% confidence intervals	SSX = $\sum(X_i - X_{mean})^2$	Mean ln Diameter	Mean ln Height	Mean ln Volume	Mean ln StemD
A. concolor, *C. decurrens*, *P. jeffreyi*, and *P. lambertiana*	<0.64 cm live	31	14–144	17–172	0.001–0.9	0.5–8	0.166	0.280	0.365	0.397	0.148	0.221	0.016	0.082	−0.066	−0.077	0.085	1.311	1.313	12.664	3.770	4.186	−3.166	0.689
	Live foliage	31					0.164	0.389	0.318	0.307	0.158	0.236	0.017	0.087	−0.070	−0.082	0.091	1.311	1.313	12.664	3.770	4.186	−3.166	0.689
	Total biomass	31					0.173	0.385	0.358	0.279	0.155	0.231	0.016	0.085	−0.069	−0.081	0.089	1.311	1.313	12.664	3.770	4.186	−3.166	0.689
A. concolor	<0.64 cm live	8	15–85	17–119	0.002–0.2	0.5–3	0.063	0.175	0.066	0.539	0.075	0.408	−0.162	0.734	0.047	−0.653	0.605	1.440	1.476	2.405	3.562	3.762	−3.964	0.149
	Live foliage	8					0.194	0.474	0.149	0.605	0.136	0.743	−0.294	1.336	0.085	−1.188	1.103	1.440	1.476	2.405	3.562	3.762	−3.964	0.149
	Total biomass	8					0.150	0.407	0.122	0.602	0.120	0.656	−0.259	1.179	0.075	−1.048	0.972	1.440	1.476	2.405	3.562	3.762	−3.964	0.149
C. decurrens	<0.64 cm live	7	20–67	35–85	0.002–0.2	0.7–3	0.117	0.616	0.582	0.434	0.142	4.393	0.124	0.259	−1.216	−0.256	0.530	1.476	1.533	1.051	3.420	3.943	−3.849	0.544
	Live foliage	7					0.071	0.805	0.662	0.345	0.080	2.468	0.069	0.145	−0.684	−0.144	0.298	1.476	1.533	1.051	3.420	3.943	−3.849	0.544
	Total biomass	7					0.080	0.821	0.693	0.270	0.086	2.667	0.075	0.157	−0.738	−0.155	0.321	1.476	1.533	1.051	3.420	3.943	−3.849	0.544
P. jeffreyi	<0.64 cm live	8	14–144	23–172	0.001–0.9	0.5–8	0.226	0.268	0.607	0.081	0.266	4.190	2.348	2.202	−3.108	−2.559	3.059	1.440	1.476	4.274	4.013	4.370	−2.443	0.991
	Live foliage	8					0.148	0.182	0.577	0.105	0.155	2.446	1.371	1.286	−1.815	−1.495	1.788	1.440	1.476	4.274	4.013	4.370	−2.443	0.991
	Total biomass	8					0.160	0.227	0.719	0.078	0.177	2.796	1.566	1.469	−2.075	−1.709	2.045	1.440	1.476	4.274	4.013	4.370	−2.443	0.991
P. lambertiana	<0.64 cm live	8	14–102	34–170	0.005–0.4	1–6	0.073	0.049	0.056	0.127	0.043	0.978	0.353	0.263	−0.517	−0.305	0.377	1.440	1.476	2.673	4.041	4.638	−2.299	1.053
	Live foliage	8					0.076	0.066	0.050	0.127	0.049	1.109	0.400	0.298	−0.586	−0.346	0.428	1.440	1.476	2.673	4.041	4.638	−2.299	1.053
	Total biomass	8					0.093	0.042	0.057	0.100	0.036	0.826	0.298	0.222	−0.436	−0.257	0.318	1.440	1.476	2.673	4.041	4.638	−2.299	1.053

The lower and upper limits are determined as exp(XB − t SE) and exp(XB + t SE), respectively. For the simple regression, XB = $a + bx$, with x = ln(crown diameter in cm), ln(tree height in cm), ln(crown volume in m^3), or ln(stem diameter in cm), depending on the regression predictor, and SE = $\sqrt{\{MSE[1 + 1/N + (x - X_{mean})^2/SSX]\}}$. For the multiple regression using both crown diameter and height, XB = $a + b_1$ln(diameter) + $b_2$ln(height), and SE = $\sqrt{\{MSE + s00 + s11 \ln(\text{diameter})^2 + s22 \ln(\text{height})^2 + 2[s01 \ln(\text{diameter}) + s02 \ln(\text{height}) + s12 \ln(\text{diameter})\ln(\text{height})]\}}$.

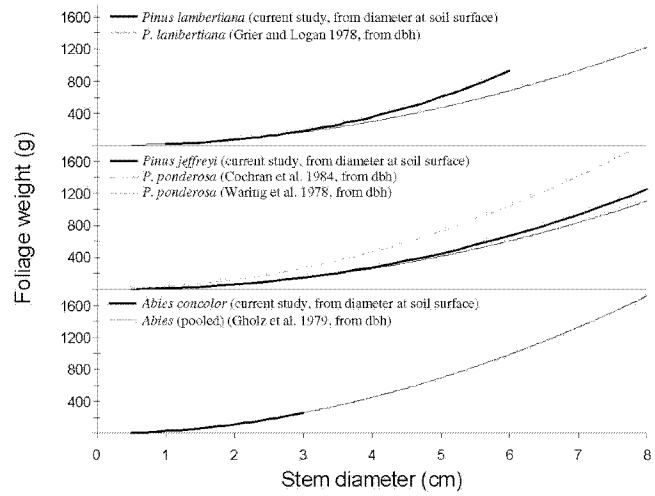

Figure 2. Biomass predictions for oven-dry conifer foliage from Sierra Nevada specimens (heavy black lines, current study) and Oregon specimens (gray lines, other studies). The equations in the current study use stem diameter at the soil surface as the independent variable, whereas the equations for the Oregon specimens use dbh as the independent variable. It is assumed that dbh (usually above any buttressing) in large trees is proportional to diameter at the soil surface in plantation seedlings and saplings with little or no buttressing. The equations for the Oregon specimens have been republished in other sources (e.g., Gholz et al. 1979, Means et al. 1996, and Jenkins et al. 2004).

very similar to those from Oregon (<20% different at 100 cm crown diameter); these taxa included *Arctostaphylos patula*, *Ceanothus* (*Ceanothus cordulatus* and *Ceanothus intergerrimus* in our study, *Ceanothus velutinus* in their study), *Chrysothamnus* (*Chrysothamnus nauseosus* and *C. parryi* combined in our study, *C. nauseosus* in their study) and *Symphoricarpos*. Our predictions for the additional two taxa (*Prunus emarginata* and currant) were 30–37% lower than those from Oregon at 100 cm crown diameter. Comparing predictions for these taxa using volume as the independent variable (Fig. 3b), half of our biomass predictions were relatively close to those from Oregon (<30% different at 0.01 m^3). The rest of the biomass predictions were significantly different (69–85% different at 0.01 m^3). Our biomass predictions based on volume yielded higher estimates than the ones from Oregon in five of the six taxa. These discrepancies may be a result of the formulas used to calculate volume; we calculated it geometrically (volume of a sphere, frustum, etc.) and the other study used length × width × height.

The equations presented in this article that use crown diameter as the independent variable were used to develop the Woody Plant Biomass Calculator on our web page (McGinnis and Keeley 2010), an easy-to-use biomass calculation tool. Those needing to calculate just a few values using crown diameter as the independent variable are encouraged to use this Web-based tool. In all tables, equations are side-by-side so that the most appropriate one can be selected to fit the needs of researchers and land managers. Also, equations for specific locations, larger branch sizes etc. are available on the Woody Biomass Calculator web page. These regression equations will be useful to managers and scientists needing to efficiently and nondestructively calculate the biomass of common Sierra Nevada woody plants.

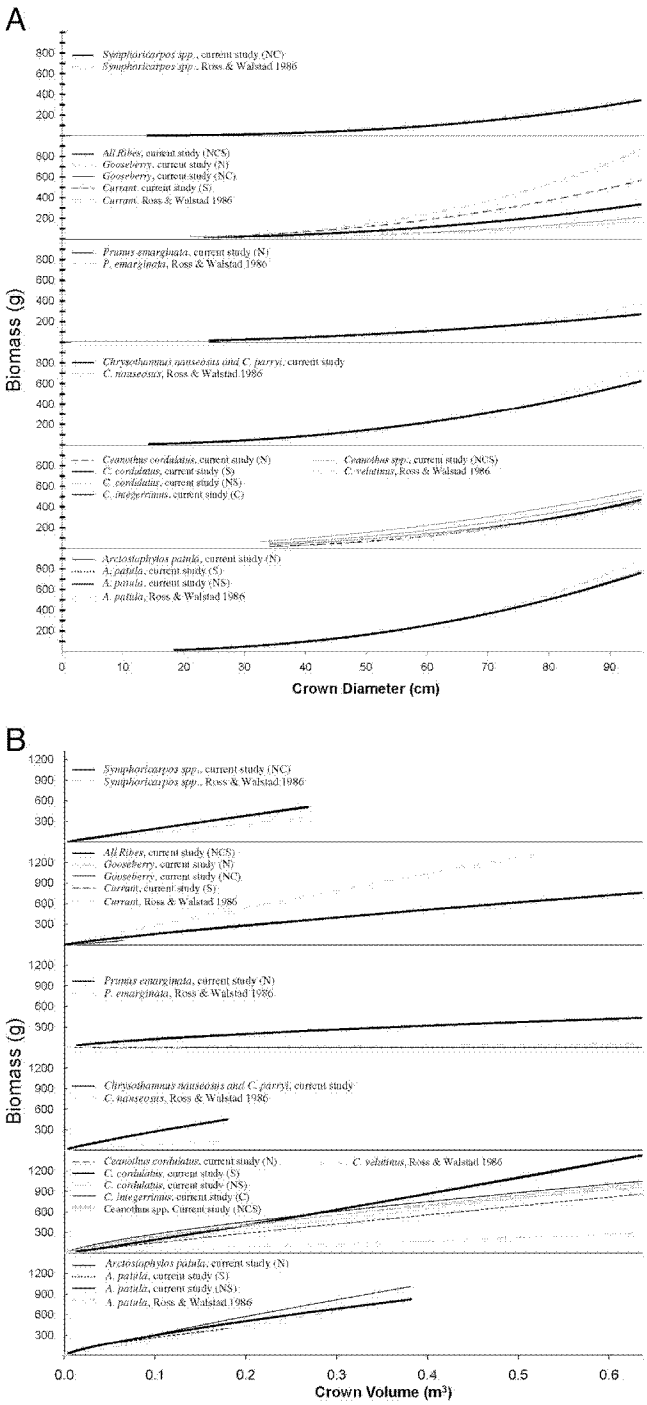

Figure 3. Total aboveground biomass predictions using crown diameter (a) and crown volume (b) as the independent variables from Sierra Nevada specimens (current study) and Oregon specimens (Ross and Walstad 1986).

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