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equations for estimating biomass and leaf area of plants in the pacific northwest

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contents

preface

These equations reflect the culmination of more than 5 years of work by the authors. However, many other scientists have contributed data through theses, other publications, and personal communications. We tried to obtain all data from work done in Oregon and Washington, but some equations required data from other states to fill holes in our own coverage. Not every species is represented, nor are all size classes or all habitats. But, with this report and a tape measure, a researcher in the field can estimate average plant weights and leaf areas for a wide range of species and sites.

All raw data and equations in Appendix A are preliminary and will be updated as new data are collected. The raw data for all our own equations and those data we could obtain for equations from other sources listed in Appendix B are available as cards, printouts, or magnetic tapes. In addition, a FORTRAN biomass function library and user's guide for programmers, written to facilitate computer manipulation of the equations, can be purchased at cost. For either data or the user's guide, contact A. T. Brown, Department of Forest Science, School of Forestry, Oregon State University, Corvallis, Oreg. 97331.

introduction

Reliable estimates of plant biomass and leaf surface area are essential for studying primary production, nutrient cycling, hydrology, wildlife management, and fire. This paper presents equations that can be used to make such estimates for most plant species—trees, shrubs, and herbs—dominant in western and central Oregon.[1] We also document the methods used for each equation (such as locations and sizes of sampled plants), summarize statistical attributes (sample sizes, variances, r^2), and reference previously published data.

Most of the equations presented here are a product of the Coniferous Forest Biome, part of the United States' participation in the International Biological Program (IBP). The original studies focused on undisturbed old-growth forests (more than 450 years old) of *Pseudotsuga menziesii.* Followup studies still underway are evaluating the responses of those same systems to perturbations, especially clearcutting, and the importance of streamside vegetation. Therefore, most equations apply best to three basic habitats, all in the western Cascade Mountains of Oregon: mature coniferous forests, streamside (riparian) zones, and clearcuttings less than 10 years old. The vegetation and microclimates of these areas have been detailed by Dyrness (1973), Franklin and Dyrness (1973), Dryness et al. (1974), and Zobel et al. (1976).

Sometimes we tried to make an equation represent a broader range of habitats. For example, Grier and Logan (1977) already used about half the data from our *Pseudotsuga menziesii* equations to derive others heavily weighted toward old-growth forests in the west-central Cascade Mountains of Oregon (Appendix B, Reference 4). Because we felt that a set of equations for predicting average plant biomass on diverse sites would be more useful than one tailored to a particular area or habitat, our *Pseudotsuga menziesii* equations are composites of five data sets collected throughout the Pacific Northwest. Note that our equations for *Pinus ponderosa, Oplopanax horridum,* and *Pinus contorta* used data from areas outside the Pacific Northwest.

[1] For a complete list of the species and their common names, refer to the CHECKLIST OF PLANTS following the appendices.

methods

The brief outline of methods, site descriptions, and sampling techniques in Appendices A and B, supplemented by Table 1, provide background for the equations we derived. All equations unless written otherwise, follow the form:

$$\ln Y = a + b \ln X,$$

where a and b are regression coefficients, Y is the dependent variable, X is the independent variable, and ln indicates logarithms to the base e.

In Appendix A, $S^2_{Y \cdot X}$ is the variance associated with an equation (residual or error mean square), and n is the sample size. Variance is either in linear space or, if data were transformed, in logarithmic space. Ranges are in untransformed linear units.

These equations may not be appropriate for all studies. A common alternative method for estimating plant biomass and leaf surface area involves clipping small plots for shrub and herb biomass. In the field, we usually combined regression estimates with limited clipping when species lacked equations or when shrub and herb species were present in limited amounts.

Because this report excludes detailed site descriptions and methods, references should be consulted before an equation is used.

Table 1.

DEFINITION OF EQUATION VARIABLES.

VARIABLE	DEFINITION
Dependent	
BFT	Total foliage biomass (includes petioles)
BLB	Live branch biomass
BST	Stem wood biomass (without bark)
BBK	Stem bark biomass
BDB	Dead branch biomass
BRT	Root biomass
BNF	New foliage biomass
BSB	Stem (bark and wood) biomass
ALS	Foliar surface area (all-sided for all species)
VWD	Stem wood volume
VBK	Stem bark volume
ANL	New foliage surface area
BTO	Total aboveground biomass (includes foliage)
BFL	Flower biomass
BWT	Total aboveground wood plus bark biomass
Independent	
DBH	Stem diameter at breast height (1.3 m)
CBA	Stem basal circumference (at litter surface)
DBA	Stem basal diameter (at litter surface)
COV	Percent cover (on 1 m^2)
NFR	Number of fronds
HTO	Plant height
LTO	Plant length (base to tip along main stem)
LLF	Leaf blade length (along midrib not including petiole)
LAF	Average frond length
VCA	Canopy volume (length x width x height)

statistics

Equation slopes and intercepts were not tested for statistically significant differences; however, regression slopes (Appendix A, variable b) indicate, for example, that differences among tree species of the same genus generally were small. Consequently, we "pooled" equations for some tree genera with very small sample sizes (e.g., *Abies, Pinus*). Furthermore, differences among foliage biomass equations for most woody evergreen broadleaves were small and probably insignificant, and the same was true for deciduous broadleaves. This indicates that equations for a species can be cautiously applied to a species of similar growth form for which equations are not provided.

Many equations are based on data from trees in very restricted habitats or with a particular trait (e.g., dominant trees only versus a cross-section of the stand including suppressed trees).

Linear least squares techniques (Draper and Smith 1969) were used to fit equations to the data. However, other techniques were used for some species. For example, nonlinear curves were fit for *Alnus rubra*, and a multiple regression technique was used for *Ceanothus velutinus*. For *Tsuga heterophylla*, some raw data originally presented in an unusual form were reanalyzed using linear least squares regression.

To obtain linearity and a constant variance, both the dependent (Y) and independent (X) variables were often transformed to natural logarithms before regression. This ln/ln form usually fit the data points as well as a linear or semilog form. However, in several cases, the latter forms were clearly superior. Ratio estimators, different transformations, or inclusion of other variables may be more desirable for particular studies. Corrections for logarithmic bias (Brownlee 1967, Baskerville 1972) may or may not be appropriate to a given study. Unless indicated otherwise, this correction term was applied to all ln/ln-transformed equations:

$$a = a + (S^2_{Y \cdot X})/2.$$

However, data included here are sufficient for deriving raw (uncorrected) equations.

caution

These equations should be used carefully. Some components may differ greatly from site to site—for example, *Rhododendron* leaf area in full sun may be less than half the area in the shade for a plant of the same diameter (Gholz 1978). Aside from such obvious differences, misuse of equation forms may cause large errors. Most importantly, least squares fits rarely yield an intercept equal to zero. Often intercepts do not significantly differ from zero and can be ignored, or intercepts within a certain interval around zero can be ignored. But careless use of a negative intercept could lead to negative values for small plants, and those values could accumulate over a whole watershed, resulting in gross underestimates. Consequently, in Appendix A, the same species often has two sets of equations, one for large and one for small plants (e.g., *Acer, Castanopsis*).

Berberis nervosa, Gaultheria shallon, and *Oxalis oregona* were sampled on 1 m^2 areas, so that percent cover on 1 m^2 areas must be input, and output from the equations will be gm^{-2} or $cm^2 m^{-2}$. Without accounting for canopy depth, these equations become specific for the western Cascade Mountains of Oregon where the canopies of these species generally are less than 0.5 m. Often canopy depth of *Gaultheria* in the Coast Range can reach 2 m, so these equations could grossly underestimate biomass.

The ranges of the independent variable (X)—that is, maximum and minimum values from the data set in Appendix A—do not necessarily mean that the equation provides reasonable numbers at these extremes. Before extrapolation beyond the data, each equation should be evaluated with examples.

For some species such as *Acer macrophyllym, Polystichum munitum*, and *Berberis nervosa*, petiolar or rachis biomass may be very large in proportion to the biomass of the leaf blades (Gholz et al. 1976). This component was not separated from foliage biomass when equations were derived. Therefore, when specific leaf areas (cm^2g^{-1}) are used to calculate leaf area, the petiolar biomass should be subtracted from the foliage biomass before leaf surface area is computed, or substantial overestimates of leaf area will result.

Because specific areas are very sensitive to microclimate, we have not included them as a way to compute leaf area from foliage biomass when no separate equation is listed for leaf area. Gholz et al. (1976), Gholz (1978), and references they cite list specific leaf areas of many species common in western Oregon. For most accurate results, these values should be developed for particular sites.

Finally, we emphasize that transformations to logarithms to the base e (or natural logarithms, ln)—**not** logarithms to the base 10 (log_{10})—have been used throughout this paper.

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appendix A — equations

These equations can be used to estimate component weight, volume, or area of Pacific Northwest plant species. As explained in the METHODS, all equations (unless written otherwise) follow the form: $\ln Y = a + b \ln X$. References cited here, detailed in Appendix B, should be consulted before equations are used. For those references in parentheses, the associated equations were copied from the reference. All other equations either are composites of data sets from published and unpublished sources or represent our original work. Variables are defined in Table 1 in the text.

Table A-1.
OVERSTORY TREES
(biomass=kg, height=m, diameters and circumferences=cm, all-sided leaf area=m^2, and Juniperus *stem volumes=cm^3)*

Y	X (range)	Species	a	b	$S^2_{y \cdot x}$	n	r^2	References
BFT	DBH (8.7-111.0)	Abies (pooled)	-3.4662	1.9278	0.159	25	0.94	2,3,(12),15
BLB	DBH		-4.8287	2.5585	0.206	26	0.95	2,3,15
BST	DBH		-3.7389	2.6825	0.085	20	0.97	
BBK	DBH		-6.1918	2.8796	0.057	20	0.98	
BFT	DBH (11.7-90.4)	Abies amabilis	-4.5487	2.1926	0.077	9	0.97	2,3,(12)
BLB	DBH		-5.2370	2.6261	0.163	9	0.96	2,3
BST	DBH		-3.5057	2.5744	0.018	14	0.99	
BBK	DBH		-6.1166	2.8421	0.049	14	0.99	
BFT	DBH (18.8-111.0)	Abies procera	-4.8728	2.1683	0.034	6	0.99	3,(12)
BLB	DBH		-4.1817	2.3324	0.199	6	0.94	3
BST	DBH		-3.7158	2.7592	0.063	6	0.99	
BBK	DBH		-6.1000	2.8943	0.059	6	0.99	
BFT	DBH (7.6-35.3)	Acer macrophyllum	-3.765	1.617	0.101	18	0.87	(4)
BLB	DBH		-4.236	2.430	0.225	18	0.88	
BDB	DBH		-2.116	1.092	1.862	18	0.15	
BST	DBH		-3.493	2.723	0.014	18	0.99	
BBK	DBH		-4.574	2.574	0.058	18	0.98	

Table A-1.
OVERSTORY TREES
(biomass=kg, height=m, diameters and circumferences=cm, all-sided leaf area=m², and Juniperus *stem volumes=cm³)*

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Alnus rubra	BSB	DBH^2xHTO/100 (5.0-300.0)	$Y = 0.02+1.60X-0.0005X^2$		NA	91	0.99	(16)
	BWT	DBH^2xHTO/100	$Y = 0.02+2.09X-0.0015X^2$		NA	119	0.98	
	BRT	DBH^2xHTO/100	$Y = 0.1+0.48X-0.0005X^2$		NA	28	NA	
	BFT	DBH^2xHTO/100 (1.3-40.8)	$Y = 0.5124+0.1298X$		0.545	66	0.64	(18)
Castanopsis chrysophylla	BFT	DBH (5.8-36.0)	-3.123	1.693	0.185	19	0.81	(4)
	BLB	DBH	-4.579	2.576	0.224	19	0.89	
	BDB	DBH	-7.124	2.883	0.538	19	0.81	
	BST	DBH	-3.708	2.658	0.044	19	0.98	
	BBK	DBH	-5.923	2.989	0.068	19	0.97	
	BNF	DBH	-4.365	1.535	0.514	19	0.56	
Chamaecyparis nootkatensis/Thuja plicata (pooled)	BFT	DBH (15.5-60.2)	-2.617	1.7824	0.085	6	0.91	2,(12)
	BLB	DBH	-3.2661	2.0877	0.071	6	0.94	2,14
	BST	DBH	-2.0927	2.1863	0.058	6	0.96	
	BBK	DBH	-4.1934	2.1101	0.055	6	0.95	
Juniperus occidentalis	BFT	CBA (14.5-273.0)	-4.231	1.5606	0.024	10	0.99	(13)
	BLB	CBA	-7.2775	2.3337	0.068	10	0.99	
	BDB	CBA	-11.5140	2.8323	0.664	10	0.91	
	BST	CBA	-8.5802	2.6389	0.029	10	0.99	
	BBK	CBA	-10.175	2.6333	0.152	10	0.99	
	ALS	CBA	-2.7536	1.5361	0.019	10	0.99	
	VWD	CBA	-0.8278	2.6006	0.058	10	0.99	
	VBK	CBA	-2.4884	2.6006	0.106	10	0.98	
Pinus (pooled)	BFT	DBH (2.5-79.5)	-3.9739	2.0039	0.257	33	0.89	4,5,14
	BLB	DBH	-5.2900	2.6524	0.216	33	0.95	
	BDB	DBH (15.5-79.5)	-3.7969	1.7426	0.129	14	0.53	
	BST	DBH	-4.2847	2.7180	0.036	14	0.98	
	BBK	DBH	-4.2062	2.2475	0.067	14	0.95	
Pinus contorta	BFT	DBH (2.5-28.7)	-3.6187	1.8362	0.230	19	0.84	(5)
	BLB	DBH	-4.6004	2.3533	0.243	19	0.89	
	BSB	DBH	-2.9849	2.4287	0.052	19	0.98	

Table A-1.
OVERSTORY TREES
(biomass=kg, height=m, diameters and circumferences=cm, all-sided leaf area=m^2, and Juniperus *stem volumes=cm^3)*

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Pinus lambertiana	BFT	DBH (20.6-43.3)	-4.0230	2.0327	0.438	5	0.52	(4)
	BLB	DBH	-7.637	3.3648	0.300	5	0.81	
	BST	DBH	-3.984	2.6667	0.038	5	0.96	
	BBK	DBH	-5.295	2.6186	0.081	5	0.91	
Pinus ponderosa	BFT	DBH (15.5-79.5)	-4.2612	2.0967	0.338	9	0.84	(12)
	BLB	DBH	-5.3855	2.7185	0.042	9	0.99	14
	BDB	DBH	(-2.5766)	1.444	NA	9	0.64	
	BST	DBH	-4.4907	2.7587	0.031	9	0.99	
	BBK	DBH	-4.2063	2.2312	0.063	9	0.97	
	BNF	DBH	(-6.3022)	2.300	NA	9	0.86	
Pseudotsuga menziesii	BFT	DBH (1.8-162.0)	-2.8462	1.7009	0.483	123	0.86	3,4,6,8,9
	BLB	DBH	-3.6941	2.1382	0.399	123	0.92	
	BDB	DBH	-3.529	1.7503	0.530	85	0.84	3,4,6,9
	BST	DBH	-3.0396	2.5951	0.096	99	0.99	
	BBK	DBH	-4.3103	2.4300	0.104	99	0.99	
	BRT	DBH (2.3-135.0)	-4.6961	2.6929	0.127	26	0.96	9,(10)
	BNF	DBH (25.9-162.0)	-5.7265	2.039	0.323	29	0.93	(4)
Tsuga heterophylla	BFT	DBH (15.3-78.0)	-4.130	2.128	0.189	18	0.96	2,3,(4)
	BLB	DBH	-5.149	2.778	0.177	18	0.98	
	BDB	DBH	-2.409	1.312	0.641	18	0.62	
	BST	DBH	-2.172	2.257	0.014	18	0.99	
	BBK	DBH	-4.373	2.258	0.019	18	0.99	
	BNF	DBH	-5.379	2.124	0.517	10	0.81	
Tsuga mertensiana	BFT	DBH (17.0-76.2)	-3.8169	1.9756	0.025	11	0.97	2,(12)
	BLB	DBH	-5.2581	2.6045	0.015	11	0.99	2
	BDB	DBH (17.0-54.6)	-9.9449	3.2845	0.012	6	0.98	
	BST	DBH (17.0-76.2)	-4.8164	2.9308	0.052	14	0.98	
	BBK	DBH	-5.5868	2.7654	0.051	14	0.97	

Table A-2.
SHRUBS[a,b]
(biomass=g, linear measurements=cm, all-sided leaf area=cm², VCA= cm³, BTO=kg)

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Acer circinatum[c]	BFT	DBA (0.6-13.1)	1.8820	1.9754	0.068	31	0.97	14
	ALS	DBA (> 3.8)	8.7070	1.9910	0.203	19	0.94	
	BLB	DBA (0.6-13.1)	1.6650	3.1510	0.138	11	0.98	
	BSB	DBA	3.4860	2.8370	0.039	11	0.99	
Acer circinatum sprouts[a]	ALS	DBA (0.9-3.8)	7.9418	2.0103	0.069	19	0.91	14
	BLB	DBA	1.2147	3.1600	0.086	6	0.97	
	BDB	DBA	0.2217	1.8691	1.880	8	0.33	
	BSB	DBA	3.1591	2.5335	0.066	20	0.94	
Acer macrophyllum sprouts[d]	BFT	DBA (0.4-7.2)	2.2326	1.9862	0.192	27	0.89	14
	ALS	DBA	7.9855	1.9594	0.161	27	0.91	
	BLB	DBA (0.7-7.2)	1.0728	2.9121	1.375	22	0.67	
	BSB	DBA (0.4-7.2)	2.3113	2.9479	0.156	27	0.96	
Artemesia tridentata	BFT	VCA (22680.0-2732100.0)	Y = 43.0+0.0000907X		NA	20	0.68	(1)
	BWT	VCA	Y = 128.0+0.000603X		NA	20	0.80	
Castanopsis chrysophylla[d]	BFT	DBA (0.4-5.5)	2.6399	1.8902	0.620	30	0.77	14
	BNF	DBA	1.8665	2.4396	1.147	30	0.75	
	ALS	DBA	7.6143	1.8783	0.650	30	0.76	
	ANL	DBA	6.9230	2.3730	1.155	30	0.74	
	BLB	DBA (0.6-5.5)	2.0395	2.7069	0.394	24	0.90	
	BDB	DBA	0.8999	2.2876	0.731	22	0.75	
	BSB	DBA (0.4-5.5)	2.9577	2.6103	0.174	30	0.96	

Table A-2.
SHRUBS[a,b]
(biomass=g, linear measurements=cm, all-sided leaf area=cm², VCA= cm³, BTO=kg)

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Ceanothus velutinus[e] var. velutinus	$\ln(BTO) = -0.3803 + 0.003278(LTO) - 0.2078(\frac{DBA}{2})^2 + 3.095(DBA)^{1/2}$				0.061	43	0.96	
	$\ln(ANL) = 1.2339 - 1.1163(DBA) + 6.894\,(DBA)^{1/2}$ for individual stems < 7.0 cm DBA				0.211	43	0.85	
	BRT (> 0.4 cm for whole plants, kg) = 0.318+0.1986(BTO summed over all stems of one plant)							
					0.271	24	0.84	
Cornus nuttallii sprouts[d]	BFT	DBA (0.4-3.2)	2.7920	1.8685	0.160	25	0.84	14
	ALS	DBA	8.3514	1.7920	0.228	25	0.77	
	BLB	DBA	2.2606	2.8737	0.322	25	0.84	
	BSB	DBA	3.2943	2.0625	0.289	25	0.78	
Corylus californica[c]	BFT	DBA (0.7-2.9)	2.4170	2.040	0.200	20	0.82	14
	ALS	DBA	8.502	2.063	0.218	20	0.81	
	BWT	DBA	3.7190	2.989	0.240	20	0.89	
Holodiscus discolor[c]	BFT	DBA (0.5-3.1)	2.1600	1.982	0.125	20	0.89	14
	ALS	DBA	3.782	2.743	0.166	20	0.86	
	BWT	DBA	8.0020	2.030	0.048	20	0.98	
Oplopanax horridum[f]	BFT	DBA NA	(1.45)	2.11	NA	38	0.82	
	BSB	DBA	(1.59)	3.34	NA	38	0.94	
Rhododendron macrophyllum	BFT	DBA (0.3-7.0)	2.6560	1.8268	0.249	51	0.99	(11)
	ALS	DBA	8.2764	1.8518	0.234	108	0.90	(11)
	BWT	DBA (0.5-4.4)	3.2447	2.6527	0.005	12	0.99	11

Table A-2.
SHRUBS[a,b]
(biomass=g, linear measurements=cm, all-sided leaf area=cm², VCA= cm³, BTO=kg)

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Rhododendron macrophyllum sprouts[d]	BFT	DBA (0.4-1.6)	2.5074	1.7522	0.165	20	0.74	14
	BNF	DBA	1.7591	1.5438	0.146	20	0.72	
	ALS	DBA	7.4783	1.6745	0.183	20	0.70	
	ANL	DBA	6.8370	1.4561	0.195	20	0.63	
	BLB	DBA	1.0854	4.0389	1.191	20	0.45	
	BSB	DBA	2.7470	2.3164	0.231	20	0.78	
	BFT	DBA (> 1.6)	2.5918	1.6709	0.419	113	0.76	(11)
	ALS	DBA	7.4143	1.6628	0.394	54	0.74	
Ribes bracteosum[g]	BFT	DBA (0.6-3.2)	2.2116	2.0127	0.158	28	0.84	14
	BSB	DBA (0.9-3.2)	3.1839	2.4145	0.139	12	0.88	
Rubus spectabilis[g]	BFT	DBA (0.5-2.5)	2.4667	2.6596	0.322	21	0.76	14
	BSB	DBA	3.1469	2.8938	0.203	13	0.89	
Salix sitchensis[g]	BFT	DBA (1.4-6.3)	2.1706	2.5593	0.106	7	0.92	14

Table A-2.
SHRUBS[a,b]
(biomass=g, linear measurements=cm, all-sided leaf area=cm^2, VCA=cm^3, BTO=kg)

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Tsuga heterophylla	BFT(kg)	DBH (2.1-13.4)	-4.4351	2.3886	0.103	9	0.96	7
	BLB(kg)	DBH	-5.0317	2.6160	0.022	9	0.97	
	BSB(kg)	DBH	-2.0849	2.3275	0.011	9	0.99	
Vaccinium alaskaense[g,h]	BFT	DBA (0.3-3.6)	1.5368	2.3086	0.111	35	0.94	14
	ALS	DBA (0.6-3.6)	8.2600	2.3609	0.085	21	0.94	
	BWT	DBA	3.6123	2.9944	0.140	26	0.94	

[a]Includes some individual trees less than 5 cm DBH and sprouts of hardwood trees.

[b]The intercepts of all ln/ln transformed equations (except those enclosed by parentheses) have been corrected for logarithmic bias.

[c]Sampled from the understory of undisturbed mature coniferous forest in the H.J. Andrews Experimental Ecological Reserve, Blue River, Oreg.

[d]Sampled from less than 10-year-old clearcuts in mesic habitats at low elevations in the H.J. Andrews Experimental Ecological Reserve, Blue River, Oreg.

[e]Personal communication, David McNabb, Department of Forest Science, Oregon State University, Corvallis.

[f]Personal communication, Stephen Kessel, Glacier National Park, Mont.

[g]Sampled from streamside at low elevations in the H.J. Andrews Experimental Ecological Reserve, Blue River, Oreg.

[h]Sampled from the understory of a mature coastal Tsuga heterophylla/Picea sitchensis stand at Cascade Head Experimental Forest, Otis, Oreg.

Table A-3.
HERBS AND FERNS[a]
(biomass=g, linear measurements=cm, all-sided leaf area=cm²)

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Adiantum pedatum[b]	BFT	LTO (20.0-98.0)	ln Y = -3.4947+0.0421X		0.098	52	0.88	14
	BSB	LTO	ln Y = -4.3446+0.0496X		0.229	52	0.81	
Aralia californica[b]	BTO	DBA (1.2-3.9)	ln Y = 1.7630+1.0952X		0.067	22	0.94	14
Athyrium filix-femina[b]	BFT	NFRxLAF (2-26; 60.0-160.0)	Y = -11.223+0.0490X		490.2	21	0.80	14
Berberis nervosa[c]	BFT	COV (5-90)	Y = 14.218+1.984X		658.8	32	0.80	(17)
Blechnum spicant[b]	BFT	NFRxLAF (2-39; 35.0-100.0)	Y = -0.4345+0.0116X		2.131	28	0.92	14
Dryopteris austriaca[b]	BFT	NFRxLAF (2-10; 45.0-110.0)	Y = -3.8256+0.0469X		55.193	21	0.80	14
Epilobium angustifolium[d]	BFT	LTO (52.0-155.0)	-6.6002	1.7076	0.049	13	0.93	14
	ALS	LTO	-1.6153	1.8143	0.064	13	0.92	
	BSB	LTO	-10.348	2.4993	0.034	13	0.98	
	BTO	LTO	-7.0665	1.977	0.107	36	0.89	
Epilobium paniculatum[d]	BTO	LTO (20.0-145.0)	-9.7444	2.5495	0.380	59	0.76	14
Epilobium watsonii[b]	BTO	LTO (36.0-162.0)	ln Y = -0.67+0.02X		0.212	21	0.69	(14)
Gaultheria shallon[c]	BFT	COV (5-85)	1.5457	0.7026	0.064	32	0.83	(17)
Gaultheria shallon[c,d]	BFT	COV (2-60)	Y = 11.699+3.518X		146.3	12	0.97	14
	ALS	COV	Y = 2616.3+558.91X		1.196×10^5	12	0.91	
	BSB	COV	Y = 2.4566+1.1425X		20.18	12	0.95	
Oxalis oregana[c]	BFT	COV (5-100)	Y = 0.4625X		2.200	10	0.96	(17)

Table A-3.
HERBS AND FERNS[a]
(biomass=g, linear measurements=cm, all-sided leaf area=cm^2)

Species	Y	X (range)	a	b	$S^2_{y \cdot x}$	n	r^2	References
Petasites frigidus[b]	BTO	LLF (5.0-23.0)	ln Y = -2.9438+0.2205X		0.077	41	0.94	14
Polystichum munitum	BFT	NFRxLAF (4-70; 34.0-130.0)	Y = -2.5695+0.0643X		1162.6	41	0.90	(17)
Pteridium aquilinum[d,e]	BFT	DBA (0.33-1.12)	3.1703	2.1433	0.079	19	0.90	
	ALS	DBA	8.9720	2.0719	0.092	19	0.88	
	BSB	DBA	2.8907	2.8368	0.070	19	0.95	
Senecio sylvaticus[d]	BFT	LTO (24.0-102.0)	-14.0035	3.4393	0.535	38	0.79	14
	ALS	LTO	-11.1395	3.9347	0.699	38	0.79	
	BSB	LTO	-16.446	4.2545	0.682	38	0.82	
	BFL	LTO	-18.447	4.6583	0.650	38	0.85	
	BRT	LTO	-14.8785	3.8645	1.091	37	0.69	
Stachys cooleyae[b]	BTO	LTO (40.0-140.0)	-7.4680	1.930	0.090	37	0.79	14
Xerophyllum tenax	BFT	$(DBA)^2$xLLF (2.0-26.0; 40.0-80.0)	Y = 18.873+0.0280X		150.4	22	0.94	(17)

[a]The intercepts of all ln/ln transformed equations (except those enclosed by parentheses) have been corrected for logarithmic bias.

[b]Sampled from streamside at low elevations in the H.J. Andrews Experimental Ecological Reserve, Blue River, Oreg.

[c]Sampled with a 1-m^2 frame so that biomass values are actually g m^{-2}.

[d]Sampled from less than 10-year-old clearcuts in mesic habitats at low elevations in the H.J. Andrews Experimental Ecological Reserve, Blue River, Oreg.

[e]Personal communication, Michelle Meyer, Department of Forest Science, Oregon State University, Corvallis.

appendix B — references

1 **URESK, D. W., R. O. GILBERT, and W. H. RICKARD. 1977. Sampling big sagebrush for phytomass. J. Range Manage. 30(4):311-314.**

Artemisia tridentata var. *tridentata*:

Linear regression equations were derived from a double sampling at the Arid Lands Ecology Reserve near Hanford, Washington. After maximum canopy length (30-185 cm), width at right angles to length (27-142 cm), and height (28-104 cm) were measured on 20 live plants, they were 100 percent destructively analyzed.[1]

[1] For comparable data and equations, see: Harniss R. O. and R. B. Murray. 1976. Reducing bias in dryleaf weight estimates of big sagebrush. J. Range Manage. 29(5):430-432.

2 **KRUMLIK, J. G. 1974. Biomass and nutrient distribution in two old-growth forest ecosystems in south central British Columbia. M.S. thesis, Univ. B.C., Vancouver. 87 p. + App.**

Tsuga heterophylla:

Eight trees (16.0-49.0 cm DBH) from near Haney, B.C. (720 m elevation, north aspect) were randomly selected from predetermined size classes. Whole trees were harvested, and branches were separated into three size classes. All material was weighed fresh in the field, then subsampled for determining wet/dry (105°C) ratios. Small twigs plus foliage-bearing twigs were clipped together and dried at 70°C, then needles were separated from the twigs. Stems were trimmed to a top diameter of 2.54 cm and cut into 10 sections of equal length. Discs were cut from the large end of each section for fresh/dry weight ratios and specific gravities. The biomass of bark and wood was estimated from specific gravities and volumes (Newton's formula).

Abies (*Abies* pooled):

See *Abies amabilis* and *Abies procera.*

Abies amabilis:

Twelve trees (32.0-76.2 cm DBH) were selected near Squamish, B.C. (1,500 m elevation, south aspect). Branch biomass was assumed to be 30 percent of twig-plus-foliage biomass; for other methods, see *Tsuga heterophylla*.

Chamaecyparis nootkatensis:

Four trees (23.1-60.2 cm DBH) from Haney, B.C. (720 m elevation, north aspect) were used for the *Chamaecyparis/Thuja* equations. Foliage and foliage-bearing twigs were not separated; otherwise, see *Tsuga heterophylla* for methods.

Thuja plicata:

One tree (53.3 cm DBH) was used for the *Chamaecyparis/Thuja* stem biomass equation from Haney, B.C. See *Tsuga heterophylla* for discussion.

Tsuga mertensiana:

Eight trees (32.0-76.2 cm DBH) were used (five with foliage and branch data) from Squamish B.C. (1,500 m elevation, south aspect). See *Tsuga heterophylla* for methods.

3 **FUJIMORI, T., S. KAWANABE, H. SAITO, C. C. GRIER, and T. SHIDEI. 1976. Biomass and primary production in forests of three major vegetation zones of the northwestern United States. J. Jpn. For. Soc. 58(10):360-373.**

Pseudotsuga menziesii:

Ten trees (28.5-99.0 cm DBH) from near Blue River, Oregon (450 m elevation) and four trees from Wildcat Mountain Research Natural Area (1,300 m elevation), north of Blue River, were selected in proportion to the number of trees of each species in 10 cm DBH classes on a 0.405-ha plot. Whole trees were harvested, and dry weights were determined by the stratified clip method.[2] Branches and foliage plus foliage-bearing twigs were separated from stem sections 3 to 4 m long. New and old twigs-plus-foliage for the samples were separated before fresh weighing. In the field, 100-percent fresh weights were determined, and samples were taken for fresh/dry (70°C) ratios and twig/foliage ratios. Specific gravities of wood and bark were determined from discs cut off the stems at the base of each section. Stem and bark biomass was estimated from specific gravities and volumes (Smalian's Rule) applied to each section.

[2] Monsi, M., and T. Saeki. 1953. Uber den Lichtfaktar in den Pflanzengesellschaften und Sline Bedeutung für die Staffproduktion. Jpn. J. Bot. 14:22-52.

Abies amabilis:

Two trees (11.7 and 19.4 cm DBH) were cut at the Wildcat Mountain Research Natural Area (1,300 m elevation) north of Blue River, Oregon. See *Pseudotsuga menziesii* for methods.

Abies procera:

Six trees (19.0-111.0 cm DBH) were selected from Wildcat Mountain Research Natural Area (1,300 m elevation) north of Blue River, Oregon. See *Pseudotsuga menziesii* for methods.

Tsuga heterophylla:

One tree (15.3 cm DBH) was used from Blue River, Oregon (450 m elevation). See *Pseudotsuga menziesii* for methods.

4 **GRIER, C. C., and R. S. LOGAN. 1978. Old-growth Douglas-fir communities of a western Oregon watershed: biomass distribution and production budgets. Ecol. Monogr. 47(4): 373-400.**

Acer macrophyllum:

All 18 trees (7.6-35.3 cm DBH) were selected from various modal sites in the H. J. Andrews Experimental Ecological Reserve (400-500 m elevation) near Blue River, Oregon. See reference 3, *Pseudotsuga menziesii*, for methods.

Castanopsis chrysophylla:

All 19 trees of this species (5.8-36.0 cm DBH) were from the H. J. Andrews Experimental Ecological Reserve (500 m elevation), Blue River, Oregon. See reference 3, *Pseudotsuga menziesii*, for methods except that new and old foliage were hand-separated in the field before the fresh weighing.

Pinus lambertiana:

All five trees (20.6-43.3 cm DBH) of this species were from the H. J. Andrews Experimental Ecological Reserve (500 m elevation), Blue River, Oregon. See reference 3, *Pseudotsuga menziesii*, for methods.

Pseudotsuga menziesii:

Five trees (78.0-162.0 cm DBH) were from the H. J. Andrews Experimental Ecological Reserve (500 m elevation), Blue River, Oregon. See reference 3, *Pseudotsuga menziesii*, for methods.

5 **REID, C. P. P., J. ODEGARD, J. C. HOKENSTROM, W. J. McCONNEL, and W. E. FRAYER. 1974. Effects of clearcutting on nutrient cycling in lodgepole pine forests. Res. Rep. to U.S. For. Serv. Coll. For. Nat. Resour., Colo. State Univ., Fort Collins. 321 p.**

Pinus contorta var. *latifolia*:

Nineteen whole trees (2.5-28.7 cm DBH) were harvested from Roosevelt National Forest, 80 km northwest of Fort Collins, Colorado (2,963-3,048 m elevation, north to northwest aspects). All branches, twigs, and green needles were taken to the laboratory, dried at 70°C, and weighed. At 1-m intervals along the stem, 2.5-cm thick discs were cut for determining specific gravity. Stem biomass was computed from volumes and specific gravities.

6 **HEILMAN, P. E. 1961. Effects of nitrogen fertilizer on the growth and nitrogen nutrition of low-site Douglas-fir stands. Ph.D. Dissertation, Univ. Washington, Seattle. Dissert. Abstr. No. 61-3989. 214 p.i,**

Pseudotsuga menziesii:

Seventy trees (1.8-19.0 cm DBH) were felled from 4 locations in western Washington with glacial sandy loam or loam soils (Whidbey Island, 100 m elevation; Darrington, 168 m elevation; C. L. Pack Memorial Forest, near Eatonville, 300-500 m elevation; and near Mattlock on the Olympic Peninsula). Trees were selected randomly from diameter classes representing the full range of DBH in each stand. All dead branches were removed and weighed fresh in the field. Boles were divided into 3.05 m sections (or 5 or 3 equal sections for large and small trees, respectively, at Whidbey and Mattlock). Composite samples for moisture content—taken as one branch from the second, third, and fourth or fifth whorl of each tree—were weighed fresh, dried at 70°C, and reweighed. The ratio of needle biomass to branch biomass was determined for a random branch from each stem section. These branches were first defoliated using sodium arsenite, dried at 70°C, and weighed. All remaining branches were removed and weighed fresh. Green weight of entire stems was measured in the field, and samples for moisture content were taken from each section. Samples and field fresh weights were used to calculate dry weights of needles, live and dead branches, and stem bark and wood for whole trees.

7 **FUJIMORI, T. 1971. Primary productivity of a young *Tsuga heterophylla* stand and some speculations about biomass of forest communities on the Oregon coast. U.S. For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Res. Pap. PNW-123. 11 p.**

Tsuga heterophylla:

From 55 trees on an 83-m^2 plot at Otis, Oregon (49 m elevation), 9 trees (2.3-13.4 cm DBH) were selected in direct proportion to the frequency distribution of DBH and height. See reference 3, *Pseudotsuga menziesii*, for methods.

8 **EMMINGHAM, W. H. 1974. Physiological responses of four Douglas-fir populations in three contrasting field environments. Ph.D Dissertation, Oreg. State Univ., Corvallis. 162 p.**

Pseudotsuga menziesii:

Twelve trees (4.0-12.2 cm DBH) were used from McDonald State Forest near Corvallis, Oregon (548 m elevation) and 12 trees from a provenance study plot near Mollala, Oregon (915 m elevation). Trees were cut at ground level and immersed in cacodylic acid. After needles abscised, they were shaken off the trees and weighed. Branches were then cut off and weighed, and finally the stem was weighed. Samples for determining moisture content were taken from needles, branches, and stem, then dried at 60°C, and reweighed; the original fresh weights were corrected to 60°C dry weight.

9 **DICE, S. F. 1970. The biomass and nutrient flux in a second growth Douglas-fir ecosystem. Ph.D. Dissertation, Univ. Wash., Seattle. 165 p.**

Pseudotsuga menziesii:

Ten trees (2.3-23.0 cm DBH) were used from the Cedar River Watershed, Seattle, Washington. All trees were sampled in a 0.0045-ha plot selected as representative of the spacing, subordinate vegetation, and other features of the sample area. After the trees were felled onto tarps, the crown was subdivided into three sections and the stem into 3-m sections. Live and dead branches, as well as needles plus needle-bearing twigs, were all separated from the stem, then 100 percent of all components were weighed fresh in the field. All components except the stems were taken to a laboratory and dried at 70°C; after the needles and twigs were separated, 100 percent of the components were then weighed. Stems from each of the 3-m sections were sampled for moisture content, dried at 70°, and weighed. Whole root systems were excavated intact, separated into two size classes (⩾ 1 cm and < 1 cm), dried at 70°C, and weighed. Total dry biomass of tree components was determined directly or from moisture content samples.

10 **SANTANTONIO, D., R. K. HERMANN, and W. S. OVERTON. 1977. Root biomass studies in forest ecosystems. Pedobiologia 17:131.**

Pseudotsuga menziesii:

Root systems were sampled from three trees (94-135 cm DBH) recently windthrown in the H. J. Andrews Experimental Ecological Reserve, Blue River, Oregon (450 m elevation). All root systems were mostly intact and showed no signs of root rot. The entire root systems were excavated, washed, lifted by a crane, and weighed with a dynamometer. The root systems were subsampled for dry (70°C)/fresh ratios.

Systems were corrected for breakage using a regression equation of root biomass on root broken-end diameter.

11 **GHOLZ, H. L. 1978. Assessing stress in *Rhododendron macrophyllum* through an analysis of leaf physical and chemical characteristics. Can. J. Bot. 56(5):546-556.**

Rhododendron macrophyllum:

Fifty-one plants were randomly selected from three site classes in the understory of a 450-year-old *Pseudotsuga menziesii* forest in the H. J. Andrews Experimental Ecological Reserve, Blue River, Oregon (450 m elevation). Leaves were counted by age classes of 1 year, and random samples were selected for determining average size (area) and weight. Another 57 plants from a plot in the same area (880 m elevation) were added to the leaf area equation. Twelve other plants from four plots, including some in full sun, were cut at the ground, stripped of their leaves, then dried and weighed to determine stem-plus-branch ("total wood") biomass.

12 **WARING, R. H., W. H. EMMINGHAM, H. L. GHOLZ, and C. C. GRIER. 1978. Variation in maximum leaf area of coniferous forests in Oregon and its ecological significance. For. Sci. 24:131-140.**

Pinus ponderosa, Thuja plicata, Tsuga mertensiana:

Foliage biomass equations only in this reference. See references 2 and 23 for discussion.

Abies amabilis, Abies procera, Abies **(pooled)**:

Foliage biomass equations only in this reference. See references 2, 3, and 24 for discussion.

13 **GHOLZ, H. L. 1979. Structure and productivity of a *Juniperus occidentalis* stand in the Oregon high desert. (manuscript in review).**

Juniperus occidentalis:

Ten trees (maximum CBA of 273 cm) were randomly selected as part of a double sampling procedure from three size classes on a 1-ha plot (1,356 m elevation) 40 km east of Bend, Oregon. Whole trees were sampled using methods described in reference 3, *Pseudotsuga menziesii*, except new and old foliage were not separated. Leaf area was measured on samples of the fresh green foliage, which were then dried at 70°C and weighed.

14 **This study.**

Pinus ponderosa:

Nine trees were sampled from the Fort Valley Experimental Forest near Flagstaff, Arizona. See reference 3, *Pseudotsuga menziesii*, for methods. The equation for foliage biomass was published previously in reference 19.

Thuja plicata:

Two trees (15.5 and 23.9 cm DBH) from the H. J. Andrews Experimental Ecological Reserve, Blue River, Oregon (400 m elevation) were used for the *Chamaecyparis/Thuja* equation. See reference 3, *Pseudotsuga menziesii*, for methods.

Tsuga mertensiana:

Six trees (17.0-54.6 cm dbh) were sampled at Wildcat Mountain Research Natural Area, north of Blue River, Oregon (1,300 m elevation). See reference 3, *Pseudotsuga menziesii*, for methods.

All shrubs, herbs, and ferns:

Sampling locations are in footnotes c, d, g, and h in Table A-2 and footnotes b and d in Table A-3. The destructive analyses all involved similar methods. Individual plants were measured appropriately, cut at ground level, and separated into designated components. Generally all the material was returned to the laboratory, dried at 70°C, and weighed. Sometimes, particularly on larger woody shrubs, entire components were weighed fresh in the field and then sampled for fresh/dry (70°C) ratios. Foliage biomass values always included petiolar biomass. Leaf area for each plant was determined by taking a separate fresh subsample, measuring the area with a portable LiCor surface area meter (Lambda Instrument Corp.), drying the material at 70°C, and weighing it to the nearest 0.1 mg. Then specific leaf areas ($cm^2 g^{-1}$ dry weight) were calculated and used with the dry foliage biomass to calculate leaf area per plant. All equations for leaf area represent blade area only (i.e., have had petiolar biomass subtracted from the foliage biomass before the specific areas were applied). Leaf areas are for all surfaces of the leaves.

15 **SATOO, T. 1974. Primary production relations in a young plantation of *Abies sachalinensis* in Hokkaido: materials for the studies of growth in forest stands—II. Bull. Tokyo Univ. For. No. 66:127-137.**

Abies sachalinensis:

Data from 11 trees (8.7-52.0 cm DBH) were included in the *Abies* (pooled) equations from the Tokyo (Japan) University Forest (240 m elevation). See reference 3, *Pseudotsuga menziesii*, for methods.

16 **ZAVITKOWSKI, J. and R. D. STEVENS. 1972. Primary productivity of red alder ecosystems. Ecology 53(2):235-242.**

Alnus rubra:

For each of 22 stands (dominant trees 1-25 years old) in the Coast Range of western Oregon, 3 to 10 trees were randomly selected to cover the DBH range in each stand. All stems and branches were weighed fresh in the field and subsampled for moisture content (70°C). Roots $\geqslant$ 6 mm were excavated from 28 trees, weighed fresh, and subsampled for moisture content. A correction factor of 10 percent was applied for roots $<$ 6 mm. Foliage biomass was estimated from litterfall data so that no separate equation exists for this component.

17 **GHOLZ, H. L., F. K. FITZ, and R. H. WARING. 1976. Leaf differences associated with old-growth forest communities in the western Oregon Cascades. Can. J. For. Res. 6(1):49-57.**

Polystichum munitum, Xerophyllum tenax,, Berberis nervosa, Oxalis oregona, Gaultheria shallon

All five species were sampled in partial shade at low elevations (450-600 m) in the H. J. Andrews Experimental Ecological Reserve, Blue River, Oregon. They were measured, clipped at the litter surface, then stripped of all live foliage which was dried at 70°C and weighed to 0.1 g. Basal diameter of *Xerophyllum* was the clump basal diameter, length was that of the compressed cone of leaves; *Berberis, Gaultheria,* and *Oxalis* were sampled on areas of 1 m^2.

18 **SMITH, N. J. 1977. Estimates of aboveground biomass, net primary production and energy flows in 8 to 10 year old red alder (*Alnus rubra* Bong.) ecosystems. M.S. thesis, Univ. B.C., Vancouver. 151 p.**

Alnus rubra:

an average of six trees each (4.83-17.53 cm DBH, 5.64-13.26 m height) from eight plots were harvested in July 1976 from 8- to 10-year-old natural stands on the University of British Columbia campus in Vancouver (100 m elevation). All branches $<$ 0.6 cm diameter (those bearing leaves) were removed and weighed fresh to 25 g. Three random samples were selected for determination of moisture content and twig/foliage weights. Samples were weighed to 0.01 g, dried at 70°C, and reweighed to 0.01 g. Equations are also included for estimating other plant components, but require additional measurements such as crown widths and root collar diameters *in addition to* DBH and height (see reference 16).

checklist of plants

TREES AND SHRUBS

scientific name	common name
Abies amabilis	Pacific silver fir
Abies procera	Noble fir
Acer circinatum	Vine maple
Acer macrophyllum	Bigleaf maple
Alnus rubra	Red alder
Artemisia tridentata	Big sagebrush
Castanopsis chrysophylla	Golden chinkapin
Ceanothus velutinus var. *velutinus*	Snowbrush
Chamaecyparis nootkatensis	Alaskan yellow-cedar
Cornus nutallii	Pacific dogwood
Corylus californica	California hazel
Holodiscus discolor	Ocean spray
Juniperus occidentalis	Western juniper
Oplopanax horridum	Devil's club
Pinus contorta	Lodgepole pine
Pinus lambertiana	Sugar pine
Pinus ponderosa	Ponderosa pine
Pseudotsuga menziesii	Douglas-fir
Rhododendron macrophyllum	Bigleaf rhododendron
Ribes bracteosum	Gooseberry
Rubus spectabilis	Salmonberry
Salix sitchensis	Sitka willow
Thuja plicata	Western redcedar
Tsuga heterophylla	Western hemlock
Tsuga mertensiana	Mountain hemlock
Vaccinium alaskaense	Alaskan huckleberry

HERBS AND FERNS

scientific name	common name
Adiantum pedatum	Western maidenhair-fern
Aralia californica	Elk clover
Athyrium filix-femina	Lady fern
Berberis nervosa	Oregon grape
Blechnum spicant	Deer fern
Dryopteris austriaca	Mountain woodfern
Epilobium angustifolium	Fireweed
Epilobium paniculatum	Autumn willoweed
Epilobium watsonii	Watson's willoweed
Gaultheria shallon	Salal
Oxalis oregona	Oregon oxalis
Petasites frigidus	Alpine coltsfoot
Polystichum munitum	Sword fern
Pteridium aquilinum	Bracken fern
Senecio sylvaticus	Woodland groundsel
Stachys cooleyae	Cooley's hedge nettle
Xerophyllum tenax	Bear grass