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Estimating large-root biomass from stump and breast-height diameters for Douglas-fir in western Oregon

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Abstract: Estimates of belowground biomass are fundamental to understanding carbon cycling and sequestration and the dynamics of ecological systems and in designing studies of those systems. An important belowground component of stands in the Pacific Northwest is the large-root biomass associated with mature, second-growth, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Sample Douglas-fir from four western Oregon stands were felled, and their stumps and root systems were excavated and cleaned. Biomass of all roots larger than 10 mm in diameter plus the belowground portion of the stump was determined on a dry-weight basis. Each tree was measured for stump diameter, 15 cm above the soil line, and for diameter at breast height. Regression models were constructed by using data from 82 trees from four stands. Stump diameters ranged from 24.1 to 92.5 cm, diameter at breast height ranged from 21.3 to 54.6 cm, and biomass ranged from 20.5 to 614.4 kg.

Résumé : Les estimations de la biomasse hypogée sont essentielles pour la compréhension du cyclage et de la séquestration du carbone et de la dynamique des systèmes écologiques ainsi que pour la planification d'études qui portent sur ces systèmes. Une composante hypogée importante des peuplements du Nord-Ouest américain est la forte biomasse racinaire associée aux peuplements matures de seconde venue de sapin de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco). Des tiges de sapin de Douglas de quatre peuplements de l'Ouest de l'Orégon ont été abattues et leurs souches et leurs systèmes racinaires ont été excavés et nettoyés. La biomasse de toutes les racines ayant un diamètre supérieur à 10 mm et de la portion hypogée de la souche a été déterminée sur la base de la masse anhydre. Le diamètre de la souche, à 15 cm au-dessus de la surface du sol et le diamètre à hauteur de poitrine de chaque arbre ont été mesurés. Des modèles de régression ont été construits avec les données de 82 arbres provenant des quatre peuplements. Le diamètre des souches variait de 24,1 à 92,5 cm, le diamètre à hauteur de poitrine, de 21,3 à 54,6 cm et la biomasse, de 20,5 à 614,4 kg.
[Traduit par la Rédaction]

Introduction

Estimates of biomass are fundamental to understanding the dynamics of ecological systems and in designing studies of those systems. Laminated root rot caused by *Phellinus weirii* (Murr.) Gilb. is the single most important natural disturbance agent causing long-term change in the forest ecosystems of the northwestern United States and Canada. The disease is widespread throughout the range of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Even though Douglas-fir is one of most susceptible host species, nearly all conifers are susceptible to some degree (Thies and Sturrock 1995). Although viable basidiospores are dispersed by the causal agent, they do not appear to be as important as vegetative spread in initiating new infections. Infection in a stand begins when healthy roots contact residual infested stumps and roots from the preceding stand. Studies of mitigative strategies for managing laminated root rot sometimes require estimates of the relative amount of inoculum (infected belowground biomass) on a site (Thies and Nelson 1988; Thies et al. 1994) or targetable biomass when chemicals are applied to individual Douglas-fir stumps (Thies and Nelson 1987*a*) or trees (Thies and Nelson 1987*b*). The basis for such estimates is limited. Published data with which to estimate the biomass in the belowground portion of the stump and roots of Douglas-fir are limited to three old-growth trees (Santantonio et al. 1977) and 10 saplings (Dice 1970). These data were used to develop a regression for estimating belowground biomass based on the stem diameter at breast height (DBH)(Gholz et al. 1979). Many studies of mitigative strategies are initiated after a stand has been harvested and diseased stumps are easily located; however, at that point DBH often is not available.

Until now we have estimated belowground biomass from the stump diameter (outside bark) at stump height (DSH) as measured 15 cm above the soil line. We were not aware of reports providing direct relation between stump diameter and belowground biomass for Douglas-fir. We developed a regression relation between basal area DBH and DSH for each stand and then used a reported relation between DBH and biomass (Gholz et al. 1979) to make our estimates (Thies and Nelson 1987*a*). Although this method of estimating biomass seemed our best choice at the time, it was not an appropriate statistical procedure. Each regression equation has associated error terms that are assumed to be independently and normally distributed; however, using one regression to estimate the independent variable in the second regression introduces a bias to the

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Table 1. Diameter at stump height (DSH), diameter at breast height (DBH), and large-root biomass (LRB), by site.

Site 1			Site 2		Site 3		Site 4		
DSH (cm)	DBH (cm)	LRB (kg)	DSH (cm)	LRB (kg)	DSH (cm)	LRB (kg)	DSH (cm)	DBH (cm)	LRB (kg)
27.9	24.6	38.2	25.7	23.4	24.1	24.5	27.4	21.3	33.1
27.9	22.1	47.7	36.3	95.2	24.1	31.4	30.0	22.1	38.8
30.5	24.9	53.7	41.1	136.1	26.2	20.5	30.5	22.1	31.4
30.5	26.4	54.3	54.9	157.7	28.7	34.3	30.7	25.7	36.8
30.5	26.7	73.5	79.8	614.4	29.2	34.0	31.0	26.4	38.9
33.0	24.1	52.4			31.2	40.1	38.6	31.0	93.7
33.0	27.2	50.4			33.5	39.7	39.1	30.2	73.6
33.0	28.2	52.8			33.8	53.1	41.1	33.8	96.0
35.6	28.4	85.4			36.8	86.8	41.4	34.5	112.2
38.1	29.5	107.7			41.1	75.2	43.4	32.5	76.7
38.1	31.5	102.0			43.4	113.8	47.5	41.4	121.6
38.1	30.0	72.1			47.0	149.5	47.5	34.8	110.9
38.1	33.0	110.5			47.5	137.9	48.0	35.8	114.2
38.1	29.5	64.6			48.3	150.4	48.8	40.1	123.2
40.6	32.8	138.6			48.3	158.5	49.0	37.8	129.0
40.6	40.1	168.5			49.8	189.0	49.5	36.8	134.5
40.6	36.3	182.7			49.8	145.2	49.5	38.6	141.6
40.6	32.0	106.1			54.1	124.1	49.5	37.1	108.8
40.6	31.8	146.7			54.6	150.2	50.0	39.1	132.3
43.2	35.6	97.1			54.9	181.5	50.8	35.8	138.0
43.2	35.3	61.4			55.4	281.2	52.1	40.4	142.7
45.7	35.8	141.0			57.7	256.6	52.8	38.1	144.4
48.3	41.9	205.8			63.5	265.4	53.1	40.1	179.4
					79.8	520.5	55.6	40.9	175.1
					92.5	494.8	57.9	50.5	310.1
							58.2	54.1	217.1
							64.8	52.1	229.6
							67.6	54.6	329.2
							71.4	52.6	296.9

error term. Although the bias might be negligible, we cannot determine its magnitude. It would be much more desirable to create an allometric model estimating root biomass directly from DSH.

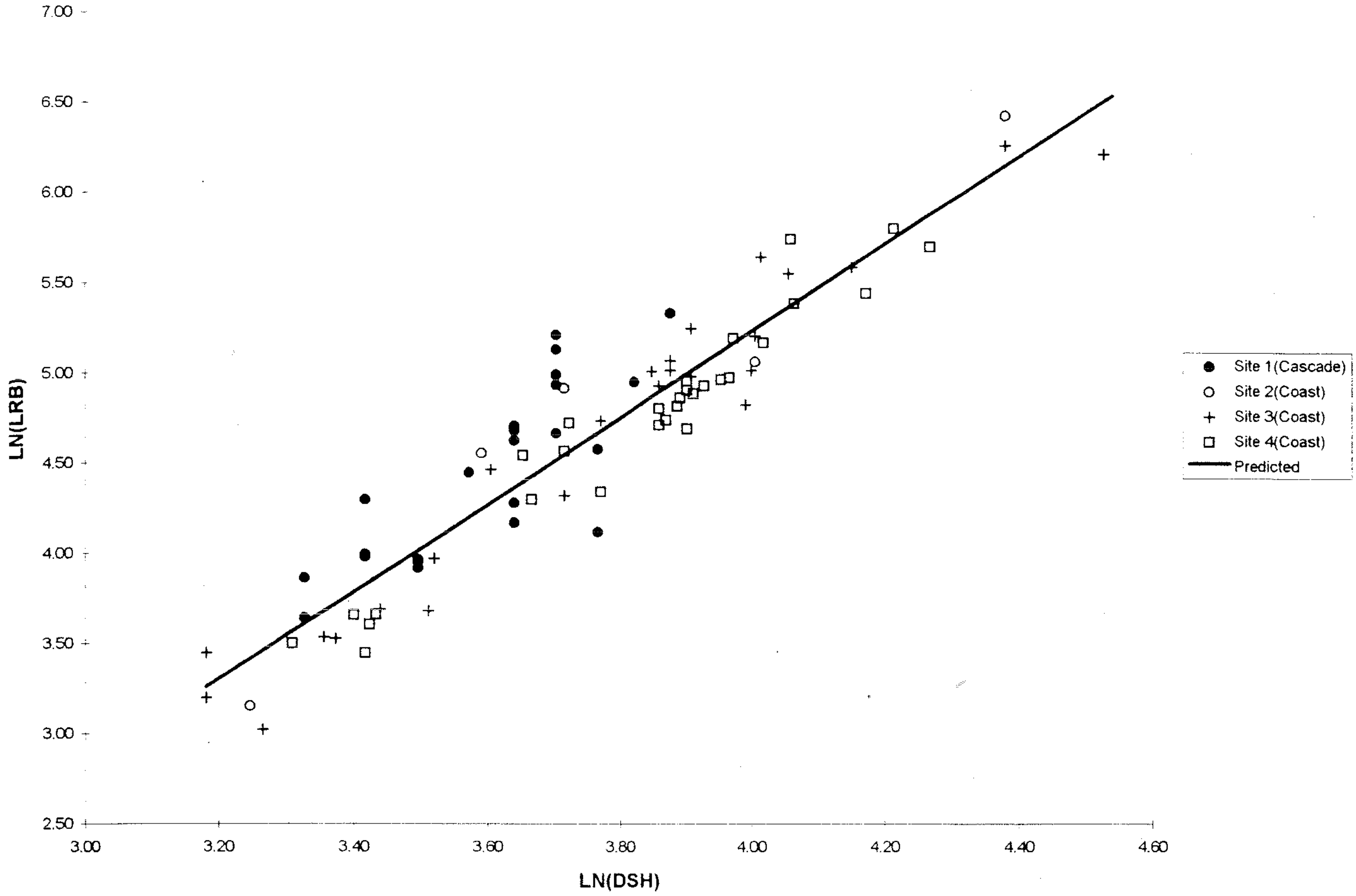
In this paper we describe the collection of belowground biomass data for healthy Douglas-fir and development of regression equations that predict that biomass based on either DSH or DBH.

Methods

Data were collected from four harvested stands in western Oregon; each stand was the site of a study of strategies for managing laminated root rot. Stand selection was opportunistic: preharvest data existed and equipment for stump removal was available. A portion of each stand was identified where there was little if any known laminated root rot. Candidate stumps were selected to be representative of the range of stump sizes in that stand. Only healthy Douglas-fir stumps on relatively flat ground, with a separation of at least 2 m from their nearest neighbors, were selected. The separation and flat ground was specified to allow for ease of excavation. Only sound stumps without visible cracks or missing bark were selected. Stumps were processed before significant drying and checking of the stump tops occurred.

Stumps on each site were processed similarly, although specific equipment differed: (1) Each stump was identified with two numbered aluminum tags. At two sites, the trees were identified, tagged, and measured for DBH before the stand was cut. (2) The stump was marked at the ground line. (3) The diameter of each stump was recorded, as measured outside the bark 15 cm above the soil with a diameter tape. (4) Each stump and root system was excavated so as to avoid loss of wood or bark. Care was taken to note any roots that had broken off, and the residual piece was immediately retrieved. The process of excavating stumps with log hooks (Thies 1984) or an excavator (Thies 1995) is explained in detail elsewhere. (5) Hand tools were used to remove soil and fine roots to leave intact all bark and roots greater than 10 mm in diameter. (6) The stump top was removed at the ground line and discarded. (7) The stump and roots were weighed to the nearest 0.45 kg. At site 1, each stump and root system was weighed on a platform scale. At sites 2, 3, and 4, each root system was lifted with a cable attached to an excavator. Weight measurements were taken with a hanging scale of the strain-gauge load-cell type located between the stump and the excavator. (8) After weighing, each stump and

Fig. 1. Transformed data (LRB/DSH) with regression line from eq. 2 superimposed.



root system was dissected and examined to assure that the wood was sound. Any condition that would have significantly affected the weight caused that stump to be dropped from the data set. (9) Samples from each stump and root system were weighed, dried to a constant weight in a 70°C oven, and weighed again to determine green moisture content. (10) Belowground biomass, more appropriately called large-root biomass (LRB), was computed for each tree from the green field weight of the stump and roots and the moisture content of the stump and root samples. (11) DSH and DBH were each used as the independent variable in simple regressions of root biomass.

Stumps were processed at four sites, all naturally regenerated and predominantly Douglas-fir:

Site 1

Owned by Weyerhauser Co.; 3 ha; 70-year-old stand. Location: west slope of the Cascade Range near Foster, Oregon. Latitude 44°30′N; longitude 122°22′W; elevation 330 m; nearly flat; mean precipitation 155 cm (Cascadia station, Redmond 1985). Soil: Saturn clay loam, surface layer about 25 cm thick overlaying 1.5 m of dark brown gravelly loamy sand; site class III (McArdle et al. 1961). Sample: 23 stumps, range 28 to 48 cm DSH, processed August 1980; DBH was collected before stand harvest.

Site 2

Owned by VanNatta Bro. Logging; 3 ha; 47-year-old stand. Location: Oregon Coast Range near Apiary, Oregon. Latitude 46°01′N; longitude 123°04′W; elevation 420 m; slope 0–15%; mean precipitation, 145 cm (U.S. Weather Bureau 1965). Soil: Bacona silt loam; site class II (McArdle et al. 1961). Sample: 5 stumps, range 26 to 80 cm DSH, processed September 1983.

Site 3

Owned by Miami Corp., managed by Cronk and Holmes of McMinnville, Oregon; 10.5 ha; 45-year-old stand. Location: Oregon Coast Range near Grand Ronde, Oregon. Latitude 45°03′N; longitude 123°44′W; elevation 240 m; slope 0–35% southwest aspect; mean precipitation 132 cm (Willamina station, National Climatic Center 1983). Soil: McDuff silty clay loam, moderately deep well-drained soil, formed in residuum and colluvium weathered from sedimentary rock; site class III (McArdle et al. 1961). Sample: 25 stumps, range 24 to 93 cm DSH, processed October 1991.

Site 4

Owned by Willamette Industries; 12 ha; 40-year-old stand. Location: Oregon Coast Range near Yamhill, Oregon. Latitude 45°27′N; longitude 123°21′W; elevation 670 m; slope 0–35% north aspect; mean precipitation 194 cm (Haskins Dam station, National Climatic Center 1983). Soil: Hembre silt loam (dark reddish brown), Melby silt loam, and Olyic silt loam, variable depth; site class III (McArdle et al. 1961). Sample: 29 stumps, range 27 to 71 cm, processed August 1993; DBH was collected before stand harvest.

Fig. 2. Transformed data (LRB/DSH) with separate regression lines superimposed for the Cascade site and the three coastal sites. Pred., predicted.

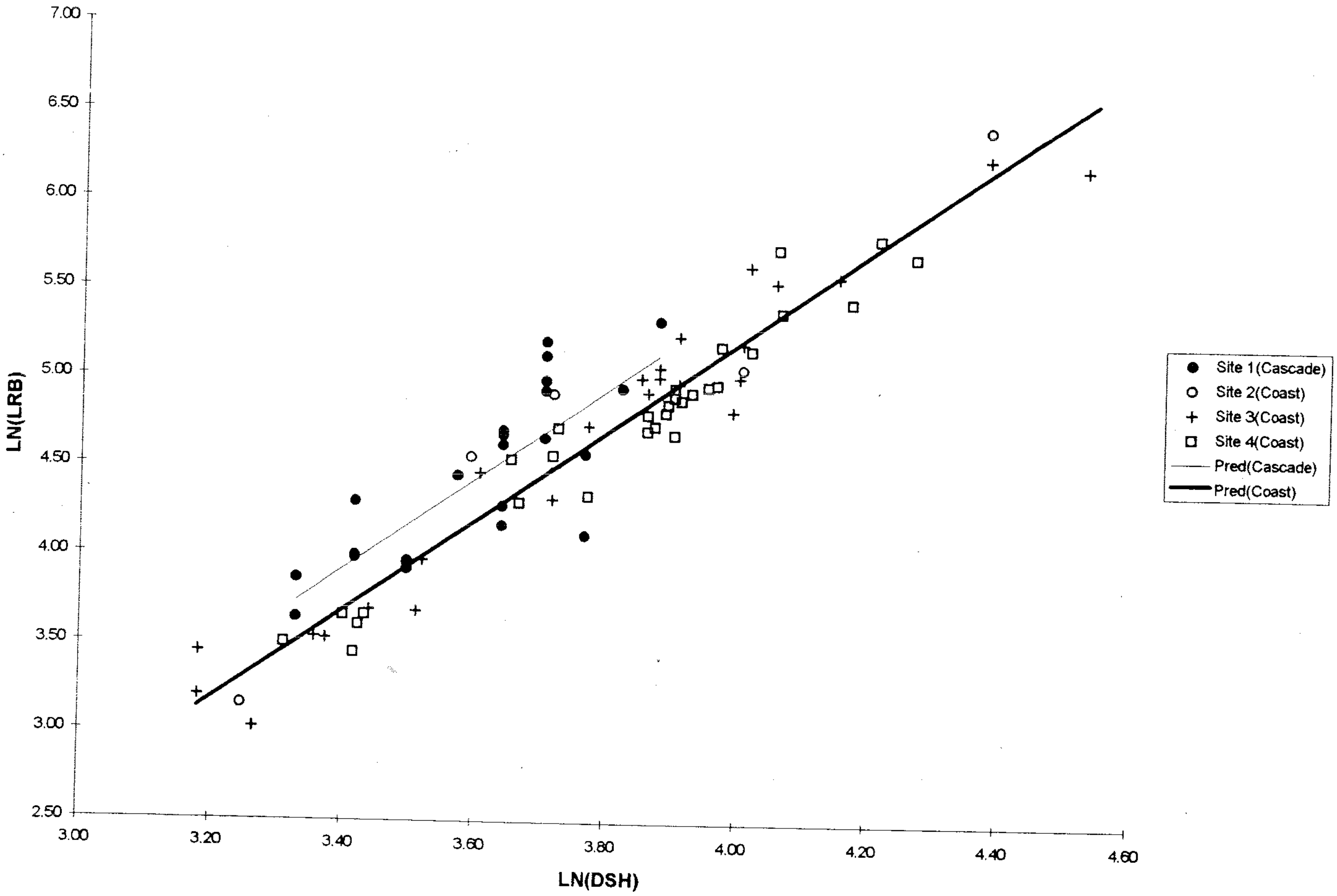


Table 2. Equations for Cascade and Coast Range sites for diameter at stump height data.

	Cascade	Coast
Intercept (uncorrected)	−4.75	−4.95
	(1.46)	(0.32)
Slope	2.55	2.54
	(0.40)	(0.08)
Variance	0.09	0.04
R^2	0.66	0.94
R^2_{pred}	0.59	0.94
N	23	59
Correction term	0.05	0.02

Note: Standard errors are given in parentheses.

Results and discussion

Raw data for this study are provided in Table 1.

Diameter at stump height

Data from the four sites (82 stumps) were used to develop the regression equation. The stumps ranged in diameter from 24.1 to 92.5 cm, and in biomass from 20.5 to 614.4 kg ovendry weight. Inspection of a graph of the raw data showed the possible presence of heterogeneous variance, and possibly nonlinearity. This heterogeneity of variance was later confirmed by using White's test (H_0: homogeneous variance, $p < 0.005$) (Kmenta 1986). Natural logarithmic transformations of both the response (LRB) and predictor (DSH) variables were applied to correct for the heterogeneity of variance and nonlinearity before any further analysis was performed (Baskerville 1972; Crow and Schlaegel 1988; Draper and Smith 1981; Weisberg 1985). The following model describes the assumed relation between LRB and DSH:

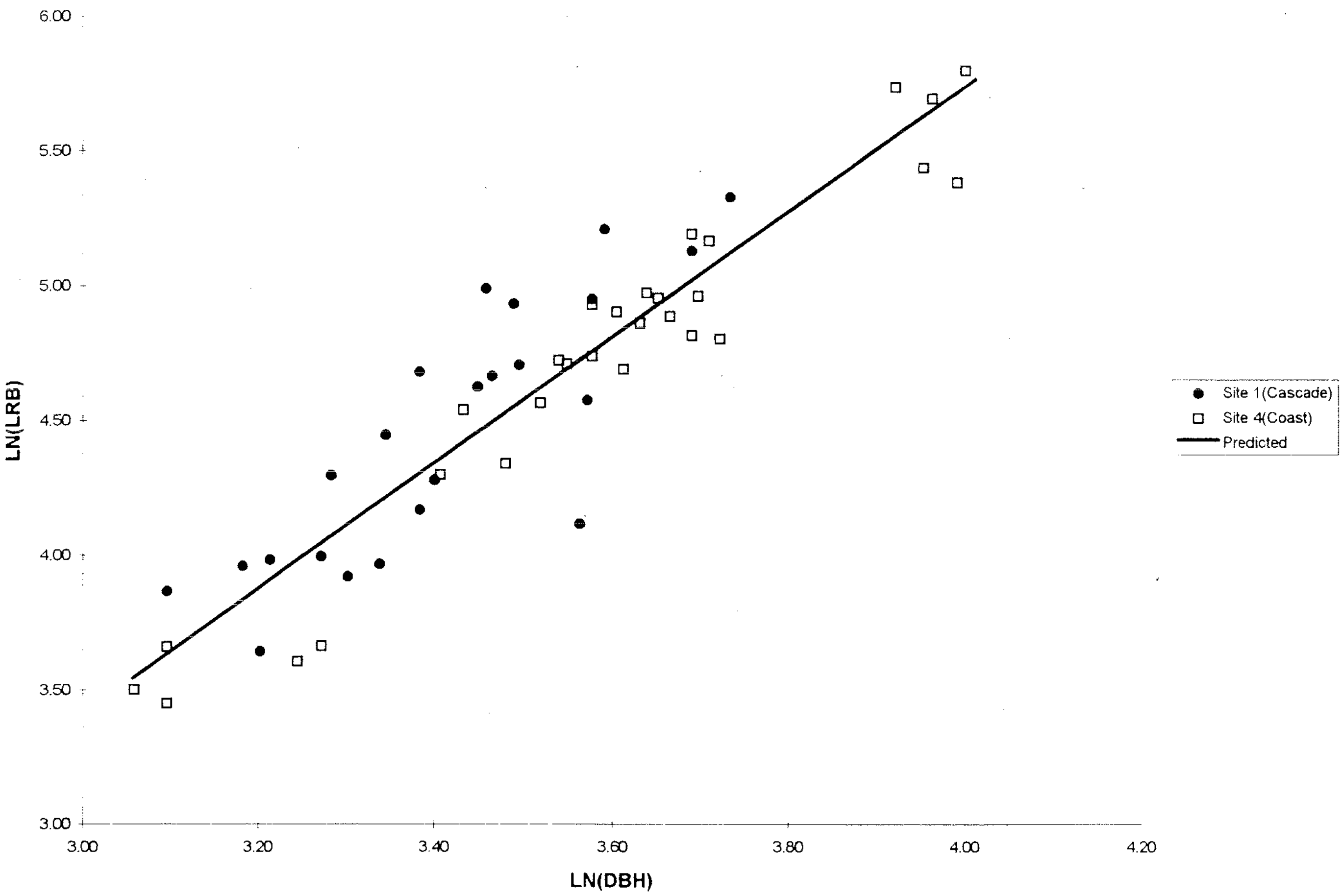
$$[1] \quad \ln(\text{LRB}_i) = \beta_0 + \beta_1 \ln(\text{DSH}_i) + \varepsilon_i$$

where ln is the natural logarithm, LRB_i is the large-root biomass in kilograms, and DSH_i is the diameter at stump height in centimetres of the ith observation, β_0 is the intercept coefficient, β_1 is the slope coefficient, and ε_i is the error associated with the ith observation. Applying ordinary least squares regression to the data from the 82 excavated root systems yielded the following estimator of LRB:

$$[2] \quad \ln(\text{LRB}) = \underset{(0.36)}{-4.41} + \underset{(0.10)}{2.41} \ln(\text{DSH})$$

The numbers in parentheses below the regression equation are standard errors of the regression coefficients. The

Fig. 3. Transformed data (LRB/DBH) with regression line from eq. 4 superimposed.



variance estimate about this regression equation is 0.06 and the coefficient of determination (R^2) is 0.89. A statistic used to validate a regression analysis (R^2_{pred}) was also computed as 0.88 (Myers 1986). This statistic is the predicted R^2 and is based on the PRESS procedure (Draper and Smith 1981; Myers 1986). Figure 1 shows the transformed data with eq. 2 superimposed.

Residuals of the transformed equation were tested for normality by using a procedure described by Kmenta (1986), which utilizes the third and fourth moments about the mean (skewness and kurtosis). Results of this test indicated that little evidence exists to support rejecting the null hypothesis of normally distributed residuals ($p = 0.27$).

Equation 2 will be used for predicting LRB in kilograms requiring a reverse transformation of the predicted result. Reverse transformation will yield an underestimate of biomass on the arithmetic scale (Baskerville 1972). Correction for bias (Baskerville 1972; Lee 1982) yields the following regression equation:

$$[3] \quad \ln(\mathrm{LRB}) = -4.38 + 2.41 \ln(\mathrm{DSH})$$

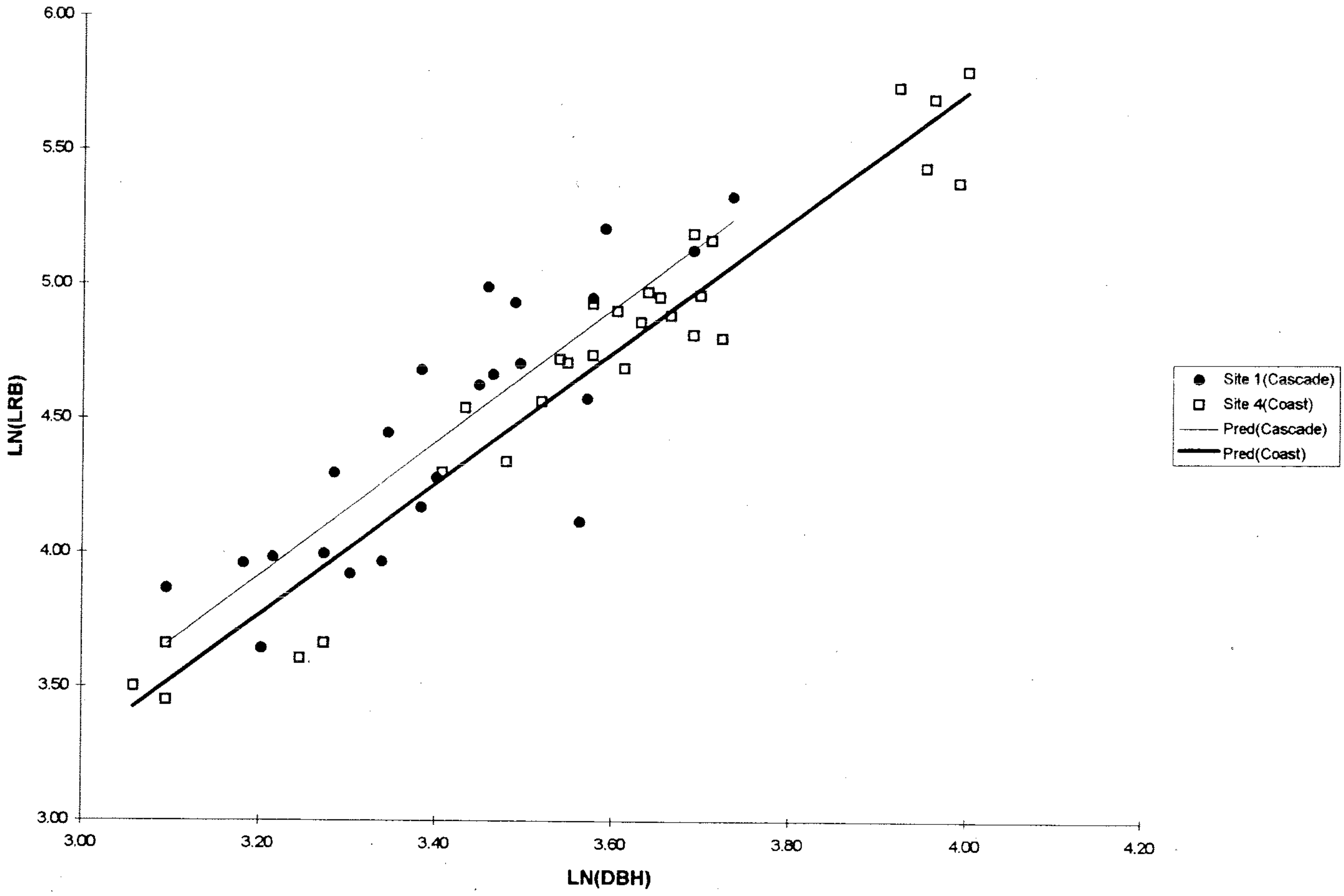
Analyses were performed to test for differences in regression relations among sites (Weisberg 1985). These tests indicated that a single equation was not sufficient to describe LRB on all sites ($p < 0.01$). Closer examination revealed that the relationship between LRB and DSH for trees from the Cascade Range site differed from the relationship between LRB and DSH for trees from the Coast Range sites. Further analysis to detect differences between Coast Range sites indicated that only small differences existed ($p = 0.23$) (Table 2). The slopes of the two equations are almost identical, but the intercepts differ by 0.20. The two equations are virtually parallel (Fig. 2). Caution is advised in using the Cascade equation because it is based on only one location.

Table 3. Equations for Cascade and Coast Range sites for diameter at breast height data.

	Cascade	Coast
Intercept (uncorrected)	−4.02	−4.04
	(1.16)	(0.43)
Slope	2.48	2.44
	(0.34)	(0.12)
Variance	0.07	0.03
R^2	0.72	0.94
R^2_{pred}	0.67	0.93
N	23	29
Correction term	0.04	0.02

Note: Standard errors are given in parentheses.

Fig. 4. Transformed data (LRB/DBH) with separate regression line superimposed for the Cascade site and the three coastal sites. Pred., predicted.



Diameter at breast height

An analysis, similar to that done with DSH, was performed using DBH as the predictor variable. DBH measurements were taken on only two sites (the Cascade site and the Yamhill site in the Coast Range). Inspection of a graph of the raw data showed the possible presence of heterogeneous variance, and possibly nonlinearity. White's test provided additional confirmation that heterogeneity of variance exists for these data (H_0: homogeneous variance $p < 0.005$) (Kmenta 1986). As with the diameter at stump height data, natural logarithmic transformations were applied to both the predictor and response variables. There were 52 observations of DBH. The following regression equation was fit:

[4] $\ln(\text{LRB}) = -3.58 + 2.33 \ln(\text{DBH})$
(0.46) (0.13)

The variance estimate about this regression equation is 0.05, the R^2 is 0.86, and R^2_{pred} is 0.85. Figure 3 shows the transformed data with eq. 4 superimposed. A test for normality also was applied to the residuals for this equation ($p = 0.79$). This test provides strong evidence to support the assumption of normally distributed residuals for this equation. The correction term for reverse transformation is 0.03, yielding the following corrected equation:

[5] $\ln(\text{LRB}) = -3.55 + 2.33 \ln(\text{DBH})$

As with the DSH equation, tests were performed by using Weisberg's (1985) method to determine whether each site required a unique equation. Because there were only two sites, the process of identifying site differences was less involved. The test for the DBH data was less conclusive, however, than the same tests for the DSH data. The comparison of regression equations indicated that a difference between sites was detectable ($p = 0.06$) (Fig. 4). The differences between sites were smaller (Table 3) for the DBH data than for the DSH data. The major difference between these two equations is the amount of variation around the regression equations, which can be seen by examining the graph of these data with the regression lines superimposed (Fig. 4). Caution is advised in using these equations, as they are based on only one location each.

Gholz et al. (1979) published a number of biomass and leaf area equations for Pacific Northwest plants. Among these equations was one for estimating LRB for Douglas-fir by using DBH as the predictor. This equation, with correction factor included, is

[6] $\ln(\text{LRB}) = -4.6961 + 2.6929 \ln(\text{DBH})$

The variance estimate for this equation is 0.127, R^2 is 0.96, and the reverse transformation correction factor (already applied) is 0.064. No standard errors for coefficients were provided.

A simple comparison of this equation to our overall DBH-based equation is to perform Student's *t*-tests on the parameter estimates for our equation using Gholz's parameter estimates as the hypothesized parameters (Weisberg 1985). These are not foolproof tests, but they should give an indication of whether the two equations are consistent. The test comparing our intercept estimate against Gholz's uncorrected intercept estimate indicates that the two are not equal ($p < 0.01$). The test comparing our slope estimate against Gholz's slope estimate also indicates that the two are not equal ($p < 0.01$). We can conclude that Gholz's equation does not fit the data from this study well.

Conclusions

The regression models proposed in this paper provide reasonable predictions of LRB given the diameter of the stem at either stump height or breast height for Douglas-fir growing in western Oregon. Although the models presented here are based on the largest available data set, the data come from a relatively small geographic area and caution therefore must be exercised in extrapolating to trees growing outside this area.

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