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Stem Growth per Unit of Leaf Area: A Measure of Tree Vigor

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ABSTRACT. The ratio of basal area growth to sapwood basal area is shown to correspond with stemwood-volume production per unit of leaf area. Analyzing 122 healthy Douglas-fir in one stand showed this ratio to be consistent among all but suppressed trees. Evaluating other stands suggests the ratio may be sensitive to environment and reflect competition. This ratio of tree vigor will aid silviculturists in determining optimum stocking or in maintaining a stand at a selected level of vigor. FOREST SCI. 26:112–117.

ADDITIONAL KEY WORDS. Stocking, leaf area index.

ANALYZING CARBON BUDGETS in trees has shown that stemwood production has less priority than root and shoot growth (Gordon and Larson 1968, Rangnekar and Forward 1973, Harris and others 1978, Fogel and Hunt 1979). Thus, the proportion of carbon allocated to stemwood production should be a measure of tree vigor. Rather than analyzing the carbon cycle directly, we may define tree vigor by assaying the amount of stemwood produced per square meter of foliage.

This general premise led us to incorporate an estimate of leaf area into a study where stem growth was being analyzed through destructive analysis of 122 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees growing in a single stand. The key to estimating leaf area was the discovery that sapwood basal area is a linear index to leaf area (Dixon 1971, Grier and Waring 1974, Waring and others 1977, Whitehead 1978).

In this paper, we first establish whether the ratio of basal area growth to sapwood basal area varies by dominant classes within a stand; then confirm whether basal area growth is linearly related to volume or biomass increment; and, finally, compare estimates of tree vigor in several stands representing different site classes and stocking.

SITE DESCRIPTIONS

The primary study area (stand 1), a 0.55-ha, 40-year-old Douglas-fir stand in the Oregon Coast Range, was harvested and examined during a study of *Phellinus weirii* (Murr.) Gilb. root rot; three other Douglas-fir stands with apparently

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TABLE 1. Site and stand characteristics of four Douglas-fir stands.

Stand	Latitude	Longitude	Elevation	Slope	Stand age	Mean site index	Mean stocking	Mean basal area
	Degrees	*Degrees*	*m*	*Percent*	*Years*	*m/100 yr*	*Trees/ha*	*m^2/ha*
1	46	123	400	15	40	52	280	30
2	44	124	530	20	45	52	500	57
3	43	123	1,070	30	125	27	500	56
4	43	123	1,070	70	125	27	450	63

healthy trees (one in the Coast Range, two in the Cascade Mountains) were analyzed for comparison (Table 1).

The climate at all sites is generally mild during the winter, when precipitation is heaviest. Less than 10 percent of annual precipitation falls during the growing season (Franklin and Dyrness 1973). Stands 3 and 4 in the Cascade Mountains are subject to considerable drought and grow on shallower soils and steeper slopes than stands 1 and 2 in the Coast Range.

METHODS

In stand 1, 150 trees were felled and their heights recorded. Up to 10 cross-sectional disks were removed from each tree, starting at stump height, breast height (dbh, 1.3 m), and intervals of not more than 5.1 m to a top diameter of 10 cm. Bark thickness and outside diameter were recorded for each disk. Sections were taken to the laboratory and stored at −18°C until radial increments could be measured. Stump sections were inspected for signs of rot and, if found, were not used in this study. A universal pH indicator which changed color was used to identify the sapwood-heartwood interface (Kutscha and Sachs 1962). For each disk, the current wood increment, 5-year wood increment, and sapwood thickness along three radii were recorded.

In stands 2, 3, and 4, no trees were felled; dbh was recorded for 10–20 trees per stand growing in plots 200–400 m^2. Growth during the last 5 years and sapwood thickness were measured on two cores taken at dbh along radii 180° apart; some smaller diameter (<20 cm) trees were cored only once. Stemwood basal area was estimated from a regression between bark thickness and dbh developed from stand 1.

Estimating Leaf Area.—One square centimeter of Douglas-fir sapwood (at dbh) is equivalent to 0.074 kg of foliage (Grier and Waring 1974), and 1 kg of foliage represents 15 m^2 of leaf surface (all surfaces) (Waring and others 1978). Therefore, 1 cm^2 of sapwood basal area approximately equals 1.1 m^2 of leaf area. Although the conversion factors may vary slightly (Gholz 1979), for our purposes here we will assume a constant relationship.

Estimating Stemwood Volume.—We calculated stemwood volume accumulated over the current (V_1) and last 5 years (V_5) from stem analyses on all 122 trees sampled in stand 1 by averaging the diameters at each end of each section and then summing the volumes of all sections in a tree.

Estimating Stemwood Biomass.—We calculated stemwood biomass accumulated over the last 5 years from ring widths measured at dbh on trees sampled in all four stands using allometric relationships established by Gholz and others (1979), where

TABLE 2. Variation in rates of basal area growth to sapwood basal area[1] *[means ± standard error (SE)] among different classes of Douglas-fir trees in stand 1.*

Dominance class	n	Height, m	Diameter, cm	BA_5/SA, cm^2/cm^2	BA_1/SA cm^2/cm^2
Dominant	11	34.6 ± 0.2	19.6 ± 2.8	0.39 ± 0.02	0.072 ± 0.005
Codominant	62	31.3 ± 0.2	17.2 ± 3.1	0.40 ± 0.01	0.075 ± 0.002
Intermediate	29	27.0 ± 0.2	12.9 ± 3.1	0.37 ± 0.02	0.067 ± 0.005
Suppressed	20	19.6 ± 0.7	9.7 ± 4.3	0.28 ± 0.03**	0.049 ± 0.006**
All trees	122	—	—	0.39 ± 0.02	0.069 ± 0.002

** Different from other dominance classes, $P < 0.01$.

[1] BA_5 = basal area growth over last 5 years. BA_1 = basal area growth over current year. SA = sapwood basal area.

$$\begin{aligned} \ln(\text{biomass, kg}) &= -3.0396 + 2.5951 \ln(\text{dbh, cm}) \\ n &= 99 \\ S_{y \cdot x} &= 0.31 \\ r^2 &= 0.99 \end{aligned} \tag{1}$$

Assuming a constant wood density, a direct conversion between volume and biomass would, of course, exist.

RESULTS

We first compared the ratio of basal area growth to sapwood basal area for the current (BA_1/SA) and last 5 (BA_5/SA) years for healthy trees in four dominance classes in stand 1 (Table 2). Although diameters and heights varied according to dominance class, the ratios were similar except for the suppressed class, which was significantly lower than the others.

TABLE 3. Linear regressions for trees sampled in stand 1.[1]

Dominance class	Variables used X	Y	B	SE	r^2
Suppressed	SA, cm^2	BA_1, cm^2	5.72×10^{-2}	0.50×10^{-2}	0.89
Others			7.45×10^{-2}	0.16×10^{-2}	0.96
Suppressed	SA, cm^2	BA_5, cm^2	3.28×10^{-1}	0.20×10^{-1}	0.94
Others			3.99×10^{-1}	0.06×10^{-1}	0.97
Suppressed	LA, m^2	V_1, m^3	1.15×10^{-4}	0.08×10^{-4}	0.92
Others			1.76×10^{-4}	0.04×10^{-4}	0.96
Suppressed	LA, m^2	V_5, m^3	5.78×10^{-4}	0.33×10^{-4}	0.95
Others			8.59×10^{-4}	0.16×10^{-4}	0.97
Suppressed	BA_1/SA	V_1/LA	1.68×10^{-3}	0.12×10^{-3}	0.92
Others			2.34×10^{-3}	0.04×10^{-3}	0.96
Suppressed	BA_5/SA	V_5/LA	1.60×10^{-3}	0.10×10^{-3}	0.94
Others			2.14×10^{-3}	0.03×10^{-3}	0.97

[1] X represents independent variables; Y, dependent variables. Regression slopes (B) were significantly different ($P < 0.01$) between suppressed and other dominance classes in all regressions.

TABLE 4. Mean production characteristics of four Douglas-fir stands.

Stand	Stemwood biomass, T/ha	Stemwood production, kg/ha/yr	Leaf area, m^2/m^2	Production/ leaf area, $kg/ha/yr/m^2$ needles	BA_5/SA ($\pm$SE), cm^2/cm^2
1	175	7,230	12.0	600	0.40 ± 0.02
2	318	5,735	17.3	330	0.25 ± 0.02
3	345	3,422	11.2	305	0.15 ± 0.03
4	377	3,088	18.0	171	0.09 ± 0.01

We pooled all trees except those in the suppressed class and evaluated regressions between sapwood basal area and basal area growth, leaf area (LA) (estimated by direct conversion from SA) and volume growth, as well as the relationships between the two kinds of regressions (Table 3). All regressions had intercepts not significantly different from 0 and were therefore forced through the origin. All but one had multiple correlation coefficients (r^2) above 0.9. Our initial observation that suppressed trees grew significantly less than others per square centimeter of sapwood (Table 2) was substantiated from all comparisons reported in Table 3. The suppressed trees were, in fact, less efficient in utilizing their foliage to produce wood.

Because suppressed trees make up only a small fraction of the trees in a stand and an even smaller proportion of the total leaf area, we feel a comparison of mean tree vigor among stands could include all trees sampled within a specified area. In Table 4, we summarize the mean production characteristics of four Douglas-fir stands representing growth on both good (stands 1 and 2) and poor (stands 3 and 4) sites as well as moderate (stands 1 and 3) and relatively high (stands 2 and 4) leaf areas. The tree vigor index (BA_5/SA) was more than 2.5 times higher on the good than the poor sites at equivalent stand leaf areas. At relatively high leaf areas, the mean tree vigor index was reduced 38–40 percent below that calculated at moderate leaf areas on both good and poor sites.

Production of biomass per unit of stand leaf area followed trends similar to those observed with the tree vigor index. In the extreme cases, stand production was 3.5 times greater per unit of leaf area in stand 1 than stand 4; the corresponding range in tree vigor was a factor of 4.4.

DISCUSSION

Our results suggest that the efficiency with which a square meter of Douglas-fir foliage converts assimilated carbon into wood may be assessed by sampling cores from tree stems and measuring annual growth increment and sapwood basal area. A detailed analysis of one stand and the small error estimates observed in the three other stands indicate that trees representing a range in dominance classes (except the suppressed) have similar vigor indices. Because suppressed trees make up a small fraction of the total, they may be included in the general sample, excluded, or weighted by the proportion they represent of the stand's leaf area in calculating mean tree vigor.

The index is sufficiently sensitive to distinguish between sites and apparently also responds to the influence of stocking. A recent study of a thinned stand of 40-year-old Douglas-fir growing in the Oregon Coast Range indicates that the tree vigor index (BA_1/SA) decreased linearly between leaf areas of 5–22 m^2/m^2 by a factor of almost 3.[1]

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[1] Newman, K. 1979. MS Thesis, School of Forestry, Oregon State University, Corvallis.

In some stands, detailed knowledge of how this tree vigor index varies among individuals has proved useful. For example, in a lodgepole pine forest attacked by mountain pine beetles, only trees with low vigor indices are apparently attacked and only those with very low vigor actually are killed (Waring and Pitman 1980). Thinning such stands does improve the vigor of the remaining trees.

Perhaps the greatest potential use of this tree vigor index may be its association with stand leaf area, which is estimated by summing sapwood basal area per hectare. As we noted, the vigor of trees may decrease with stocking, but stand growth—a product of stocking and vigor—seems to peak at some intermediate leaf area. At very low stocking, stand growth will be small, although tree vigor may be optimal for the site. At certain stocking levels, probably near half the potential leaf area, production will peak (Davidson and Donald 1958, Rees 1963, Zavitkovski and others 1974). We may be able to estimate this peak from surveys of managed and unmanaged stands. We already recognize that the potential stand leaf area varies predictably with climate (Grier and Running 1978) as well as with available soil water and other measurable variables (Waring and others 1978, Gholz 1979). This tree vigor index might serve as the means of accurately predicting stand growth on a full range of sites under differing management strategies.

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Development of Taper Functions from Variable-Top Merchantable Volume Equations

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ABSTRACT. Merchantable volume equations are now being used where the merchantable diameter desired is entered as an argument of the equation. Any equation of this type implicitly defines an associated taper function. The mathematical form of this taper function is derived for a commonly used class of variable-top merchantable volume equations. FOREST SCI. 26:117–120.

ADDITIONAL KEY WORDS. Tree form, mensuration.

DEMAERSCHALK (1972) showed how an existing total volume equation could be used in conjunction with taper data to develop a taper function that would be compatible with the volume equation. As used by Demaerschalk, the term compatible means that integration of the taper function over the limits zero to total tree height would produce the volume equation. In this paper, we will investigate the problem of developing a taper function that is compatible with a variable-top merchantable volume equation.

The class of variable-top merchantable volume equations considered here is of the form

$$V_m = V[1 - b_1 D_m{}^{b_2} D^{b_3}] \tag{1}$$

where V_m = merchantable outside-bark stem volume to an outside-bark top diameter D_m,
V = total outside-bark stem volume as given by a total volume equation (i.e., $V = g(D, H)$, where D is dbh and H is total height),
D_m = upper stem merchantability limit (expressed as outside-bark diameter), and
b_1, b_2, b_3 = regression coefficients.

Merchantable volume equations of this type have been used by Honer (1964), Burkhart (1977), and Flowers.[1] It will be shown that for any volume formula of the type shown in equation (1) there is a corresponding uniquely defined compatible taper function. The exact form of the taper function can be derived from the volume equation.

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[1] Flowers, W. R., Jr. Individual tree weight and volume equations for site prepared loblolly pine plantations in the coastal plain of the Carolinas, Georgia, and North Florida. Unpublished M S Thesis, University of Georgia, Athens, Ga. 53 p.

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