

Estimating Douglas-fir wood production from soil and climate data

E. O. ROBERTSON¹

1525 200th Street, Langley, B.C., Canada

L. A. JOZSA

Forintek Canada Corp., 6620 N.W. Marine Drive, Vancouver, B.C., Canada V6T 1X2

AND

D. L. SPITTLEHOUSE

British Columbia Ministry of Forests, Victoria, B.C., Canada V8W 3E7

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The relationships between annual tree-ring growth and growing season climate were explored, studying 70-year-old coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees in three sites of different moisture microclimates within productive forest lands. Climate data were augmented via a water balance model to calculate soil moisture deficits. Eleven ring variable components were derived via X-ray densitometry for each ring from two cores for each of 10 trees per site. First principal component scores of each ring variable were linked to climate variables (from 1951 to 1985) via multiple regression. Annual water deficit was found to account for 51% of the annual variations in ring weight. Earlywood width showed little direct climate response, and earlywood density was the least variable ring component. Latewood width was related to annual water deficit ($r^2 = 0.47$). Latewood density showed different relationships to climate variables at the different sites. Percent latewood is increased by spring rainfall and depressed by high August temperatures. The ranges between minimum to maximum and earlywood to latewood densities were comparable for all sites, indicating that there is little density variation due to site differences.

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Les relations entre la croissance annuelle des cernes et les conditions climatiques durant la saison de croissance ont été étudiées chez des Sapins de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) côtiers de 70 ans. L'étude a été réalisée dans trois stations situées dans le domaine de la forêt productive où des micro-climats étaient responsables de différents niveaux d'humidité. Les données climatiques furent incorporées dans un modèle de bilan hydrique pour calculer le déficit en eau du sol. La densitométrie au rayon-X a été utilisée pour évaluer 11 variables pour chacun des cernes annuels sur deux carottes par arbre pour chacun des 10 arbres par station. Les variables mises en évidence par l'analyse des composantes principales pour chacun des cernes furent reliées aux variables climatiques de 1951 à 1985 au moyen d'une régression multiple. Le déficit hydrique annuel expliquait 51% de la variation annuelle dans le poids des cernes. La largeur du bois initial était peu influencée de façon directe par le climat, et la densité de ce bois était la composante la moins variable des cernes annuels. La largeur du bois final était reliée au déficit hydrique annuel ($r^2 = 0,47$). La relation entre la densité du bois final et les variables climatiques variait selon les stations. La proportion de bois final est influencée à la hausse par les pluies printanières et à la baisse par les températures élevées du mois d'août. Les écarts entre les densités minimum et maximum et entre les densités du bois initial et final sont semblables pour toutes les stations indiquant qu'il y a peu de variation dans la densité attribuable aux différences entre les stations.

[Traduit par la revue]

Introduction

The British Columbia Ministry of Forests is developing growth and yield forecasts to the year 2000. The current method of projecting past growth rates to predict future growth assumes that environmental influences such as climate remain unchanged. There is increasing evidence that unchanging climate never was the case in the past and will not be the case in the future.

The probability of significant climatic change due to rising levels of carbon dioxide in the atmosphere (the greenhouse effect) is generating concern in Canada. Most global circulation models predict climatic warming in the midlatitudes, and even stronger warming in the Arctic (Schlesinger and Mitchell 1987). As a northern country, Canada must be concerned that a small change in climate could have either a positive or a negative effect on wood production (Pollard 1985, 1987).

Climate affects tree growth directly through the crown (photosynthesis and respiration) and the root system (water and nutrient uptake). Transpiration stress, resulting from a lack of soil moisture, is the major factor that limits tree growth during the summer in the Pacific Northwest area (Waring and Franklin 1979). Determining the relationships between climate and tree growth can aid forest managers in assessing the future timber supply and the sensitivity of this supply to climate change. If predictions of significant climate shifts within the time frame of our next rotation period are correct (Pollard 1985, 1987), it is essential that a mechanism be found to incorporate climate factors into the yield prediction.

Robertson and Jozsa (1988) found highly significant climate responses for 300-year-old Douglas-fir trees (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) in marginal forest growth areas in the Canadian Rocky Mountains. Multiple regression equations linked individual tree-ring width and density variables directly to daily tempera-

¹Biometric Consultant.

TABLE 1. Summary of site, stand, and tree characteristics

	Site 1 (xeric)	Site 3 (submesic)	Site 5 (subhygric)
Elevation (m)	280	210	240
Slope (%)	34	12	17
Aspect (degrees)	310	270	300
Root zone depth (m)	0.50	0.89	1.13
Site index (m @ 100 years)	31	36	48
Trees/ha	1525	1625	650
Avg. dbh (cm)	18.6	20.9	35.0
Avg. basal area (m ² /ha)	47.7	62.7	66.4
Dbh (cm)*	31.8 (26.9–36.0)	36.8 (30.0–47.8)	51.3 (43.0–60.8)
Height (m)*	29.4 (25.2–32.5)	35.2 (31.8–39.5)	44.0 (35.0–47.1)
Crown length (m)*	12.1 (9.4–15.9)	12.6 (7.3–16.0)	15.40 (10.9–19.9)
Density at breast height (g/cm ³) [†]	0.50 (0.47–0.56)	0.52 (0.45–0.61)	0.49 (0.44–0.58)

*Ten largest trees from each site. Range is given in parentheses.

[†]Basic relative density of wood for the last 35 years of growth (1951–1985). Range is given in parentheses.

ture and weekly precipitation records. However, for young vigorous forest-grown coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees (about 50 years of age), the same relationships between climate and growth were not statistically significant (Robertson and Jozsa 1987). It seemed that for these trees, the climate response is more subtle and perhaps not contingent upon the climate variables as they were represented, i.e., seasonal temperature means and precipitation totals.

A more realistic model of the processes by which climatic variation affects tree growth was needed to make reliable projections of wood quality and productivity (Running 1981; McLeod and Running 1988). Studies in stands of young Douglas-fir on Vancouver Island have shown an excellent relationship between soil moisture deficits (calculated as the difference between potential and actual evapotranspiration) and tree radial growth (Spittlehouse 1985) and site index (Giles *et al.* 1985). Similarly, correlations between the seasonal water balance and tree growth have been reported by a number of other researchers around the world (e.g., Boden 1987; Hunter and Gibson 1984; Jarvis *et al.* 1983; and McLeod and Running 1988).

The objective of this study was to use multivariate statistical analyses to examine the correspondence between elements of annual tree-ring growth and seasonal climate data. The study trees were young forest-grown coastal Douglas-fir about 70 years of age. The climate data included temperature and precipitation, but the emphasis was on soil moisture deficit.

Materials and methods

Site description

The study site consisted of three established plots on the forested northwest slope of Mesachie Mountain, which is adjacent to the British Columbia Ministry of Forests Cowichan Lake Research Station, Vancouver Island (48°50'N, 124°08'W). The plots are in an even-aged, approximately 70-year-old, stand of Douglas-fir. This natural regeneration site is in the Vancouver Island Drier Maritime Coastal Western Hemlock biogeoclimatic variant (Klinka

et al. 1984; Pojar *et al.* 1987). The plots are a subset of seven plots used by Giles (1983) and Giles *et al.* (1985) that represent a gradient of soil moisture regimes. They have been differentiated on the basis of their plant associations and forest productivity and are classed as xeric, submesic, and subhygric (relatively dry, moderate, and wet, respectively) (Klinka *et al.* 1984). Table 1 gives a summary of site characteristics and stand mensuration data based on all trees in a 20 × 20 m sample plot.

The plots have similar aspects but differ in slope and rooting depth, major physical determinants of moisture availability that are reflected in the range of site indices. Stocking density affects both the size of individual trees and the basal area of the stand. The xeric and submesic sites have 2.5 times the number of trees as the subhygric sites. The trees at the first two sites are much smaller than those at the third site. The average basal area shows that the xeric site supports 30% less stemwood productivity than the submesic site. Slower growth at the xeric site than the submesic site is attributable to transpiration stress resulting from the low soil water storage capacity of the shallow soil and possibly from nonclimatic factors such as lower soil fertility (Brix 1972).

Sample tree descriptions

Trees were selected on the basis of size and inclusion in the Giles (1983) inventory. Since soil depth and the coefficients of interception, drainage, and transpiration used in the water balance model are site specific, it was decided that sample trees should be drawn from the marked population used by Giles (1983). The 10 largest trees from each of the three sites were designated for sampling. Therefore, this is not a random sampling of the trees at the sites, but a sampling of the dominant trees. Where major defects such as scars, forks, or damaged crowns were discovered, the tree was eliminated from the sample and a dominant or codominant tree in close proximity to the 20 × 20 m plot was selected as a replacement.

Measurements of dbh, total tree height, and height to base of live crown were taken for each sample tree. Heights were estimated using a Suunto clinometer and trigonometric functions. Crown length was calculated by subtracting the height to base of live crown from total tree height (Table 1). The size gradient between sites seen in the stand measurements of Giles (1983) are reflected in the sample trees of the present study.

Increment cores were taken from each sample tree at breast height from three or four directions at 90° intervals.

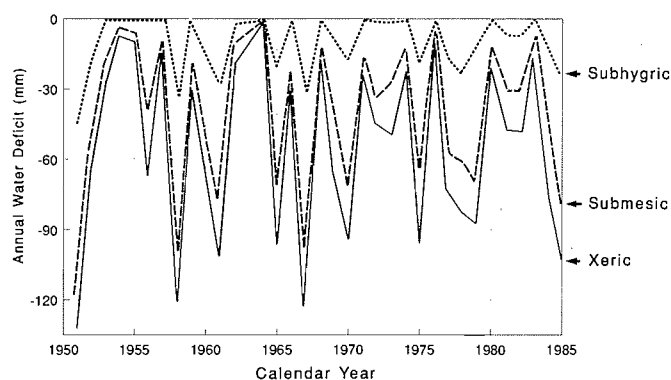


FIG. 1. Annual water deficits for three sites at Mesachie Lake.

Sample preparation for X-ray densitometry

The 5-mm increment cores were stored in a freezer until they could be extracted. The cores were extracted in a Soxhlet apparatus for 3 days in a 2:1 solution of benzene-ethanol, 3 days in ethanol, and 5 days in distilled water. The cores were then air dried before being cut to a standard thickness of 1.57 mm on a twin blade saw (Jozsa and Myronuk 1986). The samples were then cross-dated, and the two best quality cores from each tree were selected for scanning.

X-ray densitometric tree-ring data

The 60 cores (2 cores per tree $\times$ 10 trees per site $\times$ 3 sites) were scanned on a computerized direct reading X-ray densitometer (Jozsa *et al.* 1987). Direct data acquisition supplied the following eight tree-ring variables: ring width (RW), earlywood width (EW), latewood width (LW), ring density (RD), earlywood density (ED), latewood density (LD), maximum density (MXD), and minimum density (MND). A subsequent processing program was used to calculate the following three tree-ring variables: percent latewood by width (PL), ring volume (RV), and ring weight (WT). WT was expressed as the product of the RV and RD of a 1 cm long segment of the tree at breast height. Wood quality was studied by comparing average relative densities (RD, ED, and LD) and percent latewood.

Soil water balance model

The water balance model is described in detail in Spittlehouse and Black (1981), Spittlehouse (1985), and Giles *et al.* (1985). Briefly, the model calculates the changes in the daily water content of a single-layer root zone from measured rainfall and from modelled interception of rainfall by the foliage, drainage from the base of the root zone, and evapotranspiration (evaporation of intercepted water, plant transpiration, and soil surface evaporation). Surface runoff is negligible in this case. Rainfall interception is calculated as a linear function of the rainfall and stand density. Drainage is calculated as a function of the water content of the soil and soil texture. Plant transpiration and soil surface evaporation are combined (E_t) and estimated as the lesser of the atmospheric demand for moisture (E_{max}) and the ability of the soil to supply water to meet this demand. The atmospheric demand is determined from the net radiation (calculated from the sunshine data and air temperature), air temperature, and a calibration constant. It is then corrected to account for the evaporation of intercepted rain. The soil supply rate is calculated as a linear function of the fraction of extractable water in the root zone.

The seasonal water deficit is the sum of daily values of the deficit given by $E_{max} - E_t$. It is an estimate of the magnitude of the stress on the trees due to lack of water. The growing season water deficit was calculated for the period April 1 to October 31. Soil moisture is at or close to field capacity outside this period. The subhygric site was subject to recharge through subsurface flow from higher elevations until late spring. Consequently, its soil water content was maintained at field capacity until May 16. The values of

TABLE 2. Mean values of climate variables

	Xeric	Submesic	Subhygric
ATmp*	13.1	13.1	13.1
APpt*	642.5	642.5	642.5
AprT*	7.0	7.0	7.0
MayT*	11.8	11.8	11.8
JunT*	14.4	14.4	14.4
JulT*	15.5	15.5	15.5
AugT*	17.7	17.7	17.7
ESpP*	188.6	188.6	188.6
SprP*	67.9	67.9	67.9
SumP*	94.1	94.1	94.1
AWD (mm)	-52.9	-39.0	-10.1
ADay	52.0	44.1	19.4
SpWD	-15.9	-8.6	-1.3
SuWD	-48.5	-36.9	-9.9
SpDy	6.5	4.0	0.6
SuDy	45.6	40.1	18.9

NOTE: See text for a definition of the climate variables. All temperatures are in °C and precipitation and water deficits in millimetres.

*Identical climate variables at three sites.

the model coefficients are reported in Giles *et al.* (1985). A number of these parameters appear to be applicable to other Douglas-fir stands on Vancouver Island (Spittlehouse 1989). Other models, e.g., McLeod and Running (1988), cannot be used since detailed physiological data are not available.

Climate data

Daily values of minimum and maximum air temperatures, precipitation, and number of sunshine hours were obtained from the weather station at Cowichan Lake Research Station located about 1 km from the sites. The sunshine record began in 1951 and thus limited the modelling of daily water balance to the 35 years between 1951 and the collection of cores in 1985. Daily solar radiation on the horizontal for each of the three sites was derived from sunshine hours following Hay (1979), using clear-sky solar radiation as the reference value (Spittlehouse 1985). Solar radiation measured in 1980 and 1981 (Giles 1983) was used to calibrate the sunshine recorder. Correction for the slope and aspect was made using correction factors derived from an hourly solar radiation model, with topographic shading neglected (e.g., Flint and Childs 1987).

Statistical analysis

Water balance and climate data

The growing season water deficits for 1951 to 1985 are presented in Fig. 1. The daily weather data (temperature and precipitation) and water deficits were grouped into 16 climate variables for tree response evaluation. These were

ATmp, average annual growing season temperature,

April 1 to October 31

APpt, total annual growing season precipitation

AWD, annual growing season water deficit

ADay, annual growing season days with water deficit

AprT, average temperature, April 1–20

MayT, average temperature, May 5–30

JunT, average temperature, June 1–25

JulT, average temperature, June 25 to July 10

AugT, average temperature, July 20 to Aug 30

ESpP, early spring precipitation, April 1 to May 31

SprP, spring precipitation, June 1 to July 10

SumP, summer precipitation, July 11 to Sept 15

SpWD, spring water deficit, April 26 to July 10

SuWD, summer water deficit, June 21 to Sept 30

TABLE 3. Percent variation accounted for by first principal component

Ring variable	Xeric	Submesic	Subhygric
ED	50.7	38.8	29.1
LD	53.4	27.9	46.7
RD	69.4	55.5	40.6
EW	51.9	46.9	29.3
LW	63.9	51.7	40.5
RW	53.4	45.3	33.5
PL	71.6	53.1	44.5
RV	52.3	47.2	33.5
WT	60.0	49.1	34.8

NOTE: See text for a definition of the ring variables.

SpDy, spring days with water deficit, April 26 to June 20

SuDy, summer days with water deficit, June 21 to Sept 30

These variables, as well as the chosen growing season, reflect prior knowledge of the average timing of the annual growth cycle of Douglas-fir on Vancouver Island (Warrack and Joergensen 1950; Griffith 1960; Waring and Franklin 1979). Temperature and precipitation variables are the same for all three sites; water deficit and deficit days were generated by the soil water balance model and are site specific (Table 2). The influence of winter temperatures was not assessed.

Climate data were used in their original form for some of the response function development and were also used in standardized form, i.e., each variable was transformed to a mean of 0.0 and an SD of 1.0. In standardized form, the variables water deficit and days with deficit for the three sites are nearly identical, since the extreme climate years are the same for all sites, i.e., the driest year at the xeric site was also the driest year at the subhygric site.

Each climate variable was checked to see if the data were normally distributed and if there were any significant linear trends during the 35-year period. All of the temperature and precipitation variables (which are the same for all three sites) were acceptably ($p > 0.05$) normal in distribution, using the Kolmogorov-Smirnov goodness of fit statistic (Sokal and Rohlf 1969). The water deficit variables do not have symmetric, normal distributions, being skewed and kurtotic because of the high frequency of zero or very low moisture stress years. This is especially notable for the hygric site. The lower representation of highly stressed samples may increase the confidence intervals of the resulting regression statistics at the high end of the water-stress range.

Filtering tree-ring data

Visual examination of the raw data for each of the nine ring variables showed only linear growth trends during the 1951–1985 period. Therefore a linear filter was used; i.e., each core sequence was detrended by adding its residuals from linear regression to the core mean. The filtered data thus preserved the original core's mean and amplitude of variation, with only linear trends removed.

Principal components

Rather than using annual mean values for each ring variable at each site, the data array (cores $\times$ years) for each variable was reduced to its first principal component (PC)

score (one for each year). The sequence of data manipulations, from raw data, through filtering and reduction to the first PC, is described in detail in Robertson and Jozsa (1988). Filtered data were standardized (i.e., transformed to a mean of zero and SD of 1.0) prior to deriving the principal components. Earlier work with trees in highly stressed environments (Robertson and Jozsa 1988) has linked the first PC to the most limiting climatic variable and indicated that there is a general correspondence between the dominance of the first PC and the degree of climate stress. In the present study, the first PCs accounted for greater proportions of the variabilities in the xeric and submesic data than in the corresponding first PCs in the subhygric data (Table 3). This infers a stronger climatic influence on annual growth at the xeric and submesic sites and complements the field observations of less vigorous growth than in the subhygric site. A strong first PC is especially notable for RD, PL, and WT, factors that have an important impact on wood quality (Jozsa 1988).

Response function development

Fitting climate response functions for each ring variable began with an examination of the simple correlations with each climate variable and with each lagged (i.e., previous year's) ring variable. Variables whose correlation coefficient was less than 0.08 (the estimated noise level in these data) were dropped from further examination. Response functions are traditionally generated by fitting simple or multiple linear regression models of ring component variation to the climate (independent) data (Fritts 1976). This method assumes that tree responses are linear, which is often the case for severely climate limited sites. In the highly productive forest land of this study, the ring variable responses to climate were expected to be the curvilinear shapes observed when optimal conditions are flanked by reduced growth at both ends of the climate variable's range. To avoid fitting linear regression lines to such curves, plots of the xeric and subhygric data for each ring variable on each selected climate variable were visually examined for nonlinear effects.

For variables with linear patterns, simple and multiple linear regressions were developed from the climate data set and also the lagged ring variable data set. These relationships were screened for noise and the best combinations selected using the methods of Robertson and Jozsa (1988). Equations that applied consistently to all three study sites were selected in preference to equations that applied only to one or two of the sites. For significance testing, a $p < 0.05$ criterion was used unless stated otherwise.

Results

Comparison of tree-ring variables with climate variables

There were about 70 annual rings on each core (pith date 1918, bark date 1987). The xeric site cores showed much year to year variability in RW and LW. Dendrochronologists refer to these as sensitive ring series. In comparison, the other two sites (submesic and subhygric) produced very complacent sequences of annual rings. These are excellent examples of why forest-grown trees do not make good subjects for traditional climatic reconstruction compared with trees that are severely climate limited (Fritts 1976).

Ring weight

WT, the product of the volume of the annual ring times its density (for a 1 cm high segment at breast height), was

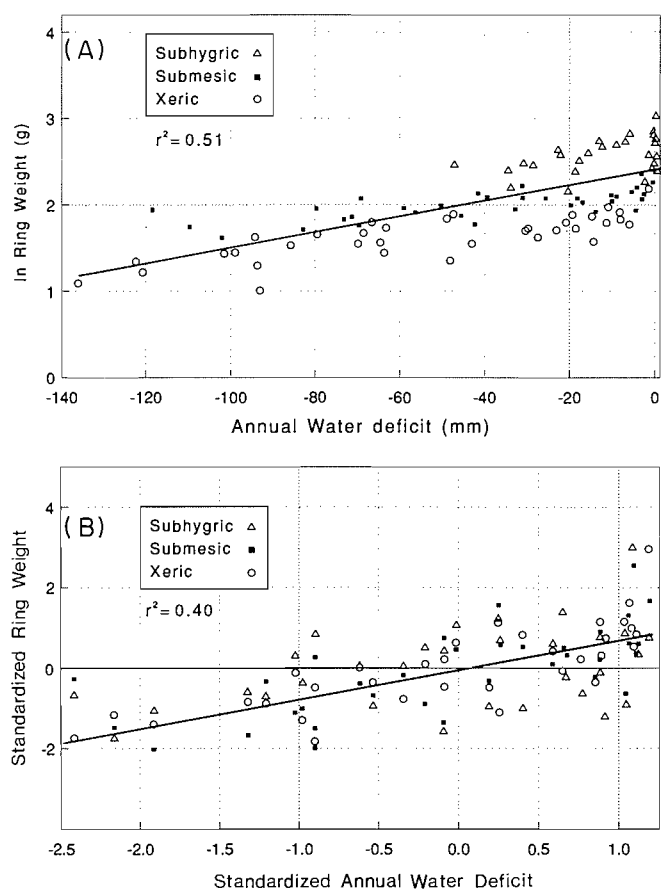


FIG. 2. (A) Relationship between ring weight and annual water deficit. (B) Relationship between standardized ring weight and standardized annual water deficit.

the first examined for responses to climate variables and previous year's ring values (lag effects). Annual water deficit, as calculated by the soil moisture model, was a factor controlling WT at the xeric and submesic sites (Fig. 2A). The observations at the subhygric site fit into the same pattern. The overall linear regression based on all sites accounted for 51% of the total variance in WT ($WT = 0.009 AWD + 2.38$). Since the study sites span the moisture range of Douglas-fir, it is likely that this relationship applies to the dominant and codominant trees of most coastal Douglas-fir stands; i.e., approximately half of the variance in annual WT could be explained by annual transpiration stress, as calculated by the model. From the graph it can be seen that additional site-specific factors accounted for some of the remaining variability, since the xeric WTs remained relatively depressed at all moisture stress levels.

A comparison of standardized WTs (i.e., all sites transformed to zero mean and unit variance) removed site-specific differences from the response analysis. In Fig. 2B standardized WT was plotted against standardized annual water deficit. Each axis unit stands for 1 SD from the mean. Over the 35-year period of investigation, years in which annual water deficits were more than 1 SD below the mean produced WTs below the mean at all sites. The 5 years, in order of decreasing dryness, were as follows: 1951, 1958, 1967, 1985, and 1961.

The average WT produced in these 5 years was depressed by 17% at the subhygric site, 18% at the submesic site, and 29% at the xeric site.

Over the 35-year period at the subhygric site, AWD alone accounted for only 16% of the variation; i.e., this site is rarely water stressed. At this site, the strongest climate influence is June temperature, which accounts for 28% of the variation in WT. A significant correlation exists between AWD and June temperature ($r = -0.58$); drier years are generally warmer. At the submesic and xeric sites there is a significant regression on June temperature, however, the relationship with July temperature is stronger ($r = -0.62$), suggesting that at these sites, the later time period is the more critical. In multiple regression equations based on pooled standardized data from all three sites, neither temperature variable complemented AWD significantly.

Multiple regression equations with two, three, and four variables were fitted to WT for each site separately. The variable combinations selected as best (using all possible combinations) were quite different for the three sites. No common equation at the two-, three-, or four-variable level could be found that was significant for all sites separately. This indicates that the patterns of influence (if any) of the other variables are not consistent at the three sites.

Since AWD controls WT, at least in part, a valid question is whether the effect is associated with a decline in RD or RV; whether earlywood, latewood, or both are involved; and whether the apportionment of the annual ring into earlywood and latewood bands is affected. Therefore, the next step of the investigation was to examine the width and density components of the separate earlywood and latewood bands.

Earlywood width

May temperature and lag effects are the major factors influencing EW. All three sites showed a decline in EW, with higher May temperatures (xeric $r = -0.47$, submesic $r = -0.46$, and subhygric $r = -0.35$). However, when unstandardized data for the three sites were combined, the regression was not significant. When the data were divided at 11.8°C (the mean May temperature), the regression in the colder half was not significant and declined significantly ($EW = -0.11 \text{ MayT} + 0.14$; $r^2 = 0.14$) in the warmer half. When standardized EW data were pooled from the three sites, the regression was significant ($r^2 = 0.16$), but there was no obvious turning point.

The xeric and submesic EW data correlated significantly with SpDy ($r = -0.47$ and $r = -0.39$), but the subhygric data had no significant correlation with SpDy.

Clearly, the response of EW is not a simple linear, univariate relationship. The variables that added independently to the May temperature response were lagged ring variables. A multiple regression equation combining MayT with these lagged variables RD, EW, and RW had $R^2 = 0.38$, for all three sites combined ($EW = 0.41 \text{ MayT} + 1.17 \text{ RD} + 1.75 \text{ EW} - 1.35 \text{ RW}$). The subhygric data alone, regressed on these four variables, gave $R^2 = 0.49$; thus in the most favorable growing areas, approximately half of the annual variation in EW seems to be determined by the previous year's growth. The xeric site had a much weaker fit to this set of variables ($R^2 = 0.19$), indicating that lag effects are not as influential at this moisture-stressed site.

Earlywood density

There was a strong negative correlation between ED and EW ($r = 0.78$). Like EW, ED showed different responses to climate and lag effects at the three sites. At the subhygric

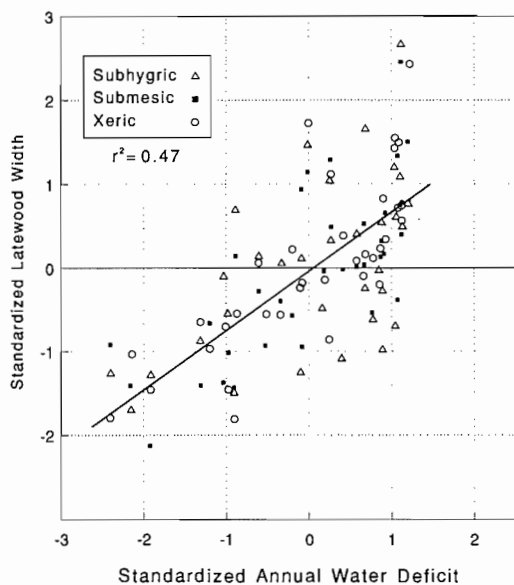


FIG. 3. Relationship between standardized latewood width and standardized annual water deficit.

site, ED was strongly correlated with ATmp ($r = -0.64$). Multiple regression on ATmp plus lagged RW also was highly significant ($R^2 = 0.55$).

At the xeric site, the strongest correlation with ED was SpDy ($r = 0.66$). The correlation of xeric ED with ATmp was not significant, nor was the corresponding correlation of subhygric ED with SpDy. When data from the three sites were combined, both simple regressions (i.e., on ATmp and on SpDy) were marginally significant at the $p > 0.05$ level, but neither was a good model of ED response. Multiple regression of standardized ED on both climate variables (ATmp and SpDy) gave a fit with $R^2 = 0.41$ for all three sites combined. The regression for each site on these two variables accounted for 64% of the variance at the xeric site, 49% at the submesic site, and 43% at the subhygric site. In the combined (three-site) equation, the partial F 's of the two climate variables were almost equal, and the partial regression coefficients ($r = -0.59$ for ATmp and 0.58 for SpDy) were almost equal except for sign. This equation is a good response function for dominant and codominant coastal Douglas-fir ED over the range of sites involved in this study. However, since the variability of annual ED is fairly narrow (the highest SD in this data set was ± 0.046 g/cm), prediction of annual ED values by itself is not of great commercial importance. (It is, however, an essential component of WT.)

Latewood width

LW appears to be most similar to WT in its responses to climate effects. A strong positive correlation with AWD at each site (xeric $r = 0.77$, submesic $r = 0.75$, subhygric $r = 0.55$) was complemented by temperature effects (subhygric $r = 0.60$ with JunT, xeric $r = 0.63$ with JulT) and lagged ring values. In the unstandardized data these relationships were sufficiently different that the combined data did not result in a significant regression. The combined standardized data showed a highly significant regression (Fig. 3) on AWD ($r^2 = 0.47$) ($LW = -0.69 AWD + 0.006$).

The best two-variable equation added lagged WT to AWD, but the improvement over AWD alone was negligible,

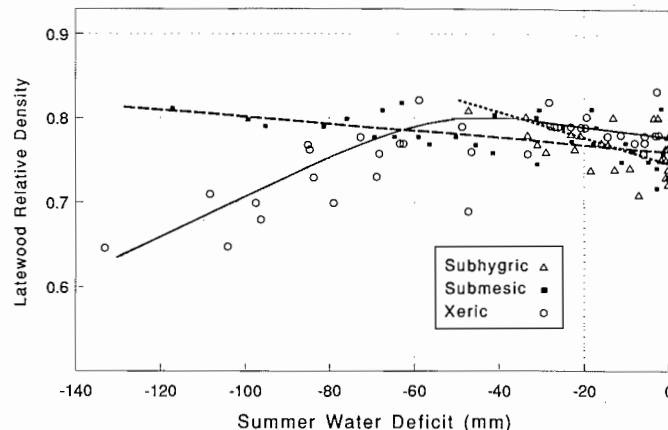


FIG. 4. Relationship between latewood relative density and summer water deficit, illustrating the three different relationships found at the three sites.

with a partial F for lagged WT of only 2.12. Thus, the univariate regression of LW and AWD is the best model for this relationship.

Like WT, LW was strongly depressed in years with high water deficits. In the five most moisture stressed years in this 35-year interval, the average LW was depressed (below the mean) by 25% at the subhygric site, 26% at the submesic site, and 37% at the xeric site. This impact of AWD on LW appears to be the dominant component of the annual WT response.

Latewood density

LD presented a complex pattern of relationships. All three sites showed strong correlations with temperature variables and also with spring and summer water deficits. One pair of variables, ATmp and SuWD, gave highly significant bivariate regressions when data for each of the three sites were examined separately, but not when the data were combined.

The site-specific equations based on unstandardized data have the regression coefficients shown in the following:

	Xeric	Submesic	Subhygric
Intercept	0.000	0.031	-0.013
ATmp	0.114	0.471	0.570
SuWD	0.818	-0.212	-0.230
R^2	0.57	0.38	0.50

Graphing the unstandardized LD data against site-specific summer water deficit data only showed that the sites have very different responses over the lower range of SuWD (Fig. 4). LD increased at the subhygric site during mildly moisture stressed summers ($LD = -0.001 HSWD + 0.75$; $r^2 = 0.25$). The increase in density had a shallower slope for the submesic site ($LD = -0.0004 MSWD + 0.77$; $r^2 = 0.26$). At the xeric site, density increased in the mildly moisture stressed years, but declined during highly moisture stressed years. This appears to be a curvilinear response, with the three sites spanning different ranges of the curve. A moderately warm, dry year leads to improved growth at the subhygric site where moisture will not limit the trees' ability to respond to increased solar radiation and temperature; but the same weather produces moisture stress at the submesic site, and the xeric site may be highly stressed.

Percent latewood

PL greatly affected WT that resulted from individual EW, ED, LW, and LD components. At the subhygric site, PL was the ring variable with the strongest response to moisture deficit data ($r = 0.60$ for both AWD and SuWD). However, at the xeric site the response to SprP was the strongest. The best bivariate equation for the three sites combined (using standardized data) involved SprP and AugT for an overall R^2 of 0.45 ($PL = 0.29 \text{ AugT} - 0.57 \text{ SprP} + 0.011$). Heavy spring rainfall increases the PL in the annual ring, whereas high August temperatures have the opposite effect.

Although these climate variables were not the ones that were selected as best for predicting the other ring components, the pattern was consistent: EW was found to be primarily a lag effect (e.g., due to previous year's growth), not directly climate controlled except in the most stressed site, whereas LW was found to be significantly reduced in moisture-stressed years.

Wood quality

The density of wood and the pattern of density differences within each ring are the main determinants of wood quality. Mean values of RD, ED, LD, MND, and MXD were calculated over all 35 years and 20 cores for each of the three sites, as shown in the following:

	RD	ED	LD	MND	MXD
Xeric	0.50	0.32	0.76	0.23	0.92
Submesic	0.52	0.31	0.78	0.21	0.93
Subhygric	0.49	0.29	0.75	0.19	0.89

A surprisingly uniform density distribution was found in spite of markedly different growth rates and site conditions.

The impact of relatively dry (1951, 1958, 1967, 1983, 1985) and wet (1954, 1961, 1964, 1980, 1981) years on ring relative density was examined for the three sites. With the exception of the xeric site, RD was homogeneous for the wet and dry 5-year periods: at the submesic site, average RD values for the wet and dry years were 0.53 and 0.51, respectively, and at the subhygric site, 0.50 and 0.48, respectively. At the xeric site the 5-year dry period produced an average RD of 0.45 and the wet period an average of 0.52.

Discussion

Relationships between ring density variables and climate variables have been reported by other workers (e.g., Conkey 1979, Brubaker 1980, Kienast *et al.* 1987, and Robertson and Jozsa 1988). However, such studies have often been restricted to trees in marginal sites that show a large sensitivity to weather and climate variation. Furthermore, they have not integrated temperature, precipitation, and radiation into biologically meaningful parameters. Our use of a water balance model to determine an index of the moisture stress on the trees has allowed the assessment of the effect of weather and climate conditions in what are normally considered complacent ring series.

This study has shown dramatic tree size differences due to different soil moisture regimes. Relationships linking annual tree-ring weight, width, and density with climate variables have been clearly demonstrated for forest-grown coastal Douglas-fir. For several of these tree parameters, especially WT and LW, the relationships were strong and

consistent over the three different soil moisture regimes examined.

The implications for growth and yield projections are notable. In this study, 5 years out of 35 have been associated with high levels of moisture stress and significant depression of WT and LW. Thus wood production is strongly climate limited in approximately 1 out of 7 years, and there is also a depression in the following year's EW, through lag effects. Two successive dry years could have a dramatic impact on growth not only in those years but also for a number of years following. Site comparisons in this study show that the cumulative effect of large moisture deficits at the xeric site over the stand lifetime has resulted in poor tree growth in dominant and codominant trees, as compared with the good productivity on the infrequently stressed subhygric site.

Changes in the frequency of water deficits through natural or man-induced changes in the climate could dramatically effect the timber supply. For example, a 20% increase in the water deficit at the submesic site would result in conditions similar to those currently occurring at the xeric site. This could be achieved with either a 10% decrease in the May to August rainfall or an increase in evaporative demand induced by a 3°C increase in mean temperature. It is unlikely that only one climate variable will change, and other variables may act to ameliorate or exacerbate the situation. The water balance model used here is a tool that can be used to take account of these interactions in the assessment of the effect of a changing climate on the water balance and future timber supply. However, the detailed regional scenarios of future climates required for such an assessment are not yet available (Gates 1985).

Conclusions

The water balance model, which transforms climate data into data of biological significance, could greatly improve our ability to model tree growth response in forest-grown coastal Douglas-fir. Significant but not high correlations were obtained between various wood quality parameters and the seasonal water deficit and selected temperature variables. The results indicate that there is some potential for incorporating climate data into predictions of growth and yield.

- BODEN, D.I. 1987. The use of actual evapotranspiration and a hydrological model to predict the growth of *Eucalyptus grandis* in South Africa. Annual Report, Institute for Commercial Forestry Research, University of Natal, Scottsville, Republic of South Africa.
- BRIX, H. 1972. Nitrogen fertilization and water effects on photosynthesis and earlywood-latewood production in Douglas-fir. *Can. J. For. Res.* 2: 467-478.
- BRUBAKER, L.B. 1980. Spatial patterns of tree growth anomalies in the Pacific Northwest. *Ecology*, 6: 798-807.
- CONKEY, L.A. 1979. Response of tree-ring density to climate in Maine, U.S.A. *Tree-Ring Bull.* 39: 29-38.
- FLINT, A.L., and CHILDS, S.W. 1987. Calculation of solar radiation in mountainous terrain. *Agric. For. Meteorol.* 40: 233-249.
- FRITTS, H.C. 1976. *Tree-rings and climate*. Academic Press, Inc., New York.
- GATES, W.L. 1985. The use of general circulation models in the analysis of ecosystem impacts of climate change. *Clim. Change*, 7: 267-284.
- GILES, D.G. 1983. Soil water regimes on a forested watershed. M.Sc. thesis, University of British Columbia, Vancouver.

- GILES, D.G., BLACK, T.A., and SPITTLEHOUSE, D.L. 1985. Determination of growing season water deficits on a forested slope using water balance analysis. *Can. J. For. Res.* **15**: 107-114.
- GRIFFITH, B.G. 1960. Seasonal variations in radial growth at breast height of some western hemlock and Douglas-fir trees, 1953-57. *For. Chron.* **36**: 391-400.
- HAY, J.E. 1979. Calculation of monthly mean solar radiation for horizontal and inclined surface. *Sol. Energy*, **23**: 301-307.
- HUNTER, I.R., and GIBSON, A.R. 1984. Predicting *Pinus radiata* site index from environmental variables. *N.Z. J. For. Sci.* **14**: 63-64.
- JARVIS, N.J., MULLINS, C.E., and MACLEOD, D.A. 1983. The prediction of evapotranspiration and growth of Sitka spruce from meteorological records. *Ann. Geophys. (Gauthier-Villars)*, **1**: 335-344.
- JOZSA, L.A. 1988. The impact of climate change and variability on wood quality. *In* Proceedings of Forest Climate '86, 17-20 Nov. 1986, Orillia, Ont. *Edited by* D.C. MacIver, R.B. Street, and A. Auclair. Atmospheric Environment Service, Downsview, Ont. pp. 189-194.
- JOZSA, L.A., and MYRONUK, R.M. 1986. Direct Reading X-ray Densitometer. Technical Report No. 21 to the Canadian Forestry Service. Forintek Canada Corp., Vancouver.
- JOZSA, L.A., RICHARDS, J.E., and JOHNSON, S.G. 1987. Calibration of Forintek Direct Reading X-ray Densitometer. Technical Report No. 36a to the Canadian Forestry Service. Forintek Canada Corp., Vancouver.
- KIENAST, F., SCHWEINGRUBER, F.H., BRAKER, O.U., and SCHAR, E. 1987. Tree-ring studies on conifers along ecological gradients and the potential of single-year analyses. *Can. J. For. Res.* **17**: 683-696.
- KLINKA, K., GREEN, R.N., COURTIN, P.J., and NUSDORFER, F.C. 1984. Site diagnosis, tree species selection and slashburning guidelines for the Vancouver Forest Region, British Columbia. British Columbia Ministry of Forests, Victoria. Land Manage. Rep. 25.
- MCLEOD, S.D., and RUNNING, S.W. 1988. Comparing site quality indices and productivity in ponderosa pine stands of western Montana. *Can. J. For. Res.* **18**: 346-352.
- POJAR, J., KLINKA, K., and MEIDINGER, D.V. 1987. Biogeoclimate ecosystem classification in British Columbia. *For. Ecol. Manage.* **22**: 119-154.
- POLLARD, D.F.W. 1985. A forestry perspective on the carbon dioxide issue. *For. Chron.* **61**: 312-318.
- _____. 1987. Forestry and climate change: facing uncertainty. *In* The E.B. Eddy Distinguished Lecture Series. Faculty of Forestry, University of Toronto Press, University of Toronto. pp. 18-39.
- ROBERTSON, E.O., and JOZSA, L.A. 1987. Estimating tree growth from climate data for Douglas-fir on Vancouver Island. Technical Report No. 32 to the Canadian Forestry Service. Forintek Canada Corp., Vancouver.
- _____. 1988. Climatic reconstruction from tree rings at Banff. *Can. J. For. Res.* **18**: 888-900.
- RUNNING, S.W. 1981. The influence of microclimate on forest productivity: a system to predict the biophysical site quality of forest land. *In* Computer techniques and meteorological data applied to problems of agriculture and forestry. *Edited by* A. Weiss. American Meteorological Society, Boston. pp. 297-316.
- SCHLESINGER, M.E., and MITCHELL, J.F.B. 1987. Climate model simulations of the equilibrium climatic response to increased carbon dioxide. *Rev. Geophys.* **25**: 760-798.
- SOKAL, R.R., and ROHLF, F.J. 1969. Biometry. W.H. Freeman and Company, New York.
- SPITTLEHOUSE, D.L. 1985. Determination of the year-to-year variation in growing season water use in a Douglas-fir stand. *In* The forest-atmosphere interaction. *Edited by* B.A. Hutchinson and B.B. Hicks. D. Reidel Publishing Co., Dordrecht, Netherlands. pp. 235-254.
- _____. 1989. Estimating evapotranspiration from land surfaces in British Columbia. *In* Estimation of areal evapotranspiration. *Edited by* T.A. Black, D.L. Spittlehouse, M.D. Novak, and D.T. Price. International Association of Hydrological Sciences, Wallingford, England. Publ. No. 177. pp. 245-256.
- SPITTLEHOUSE, D.L., and BLACK, T.A. 1981. A growing season water balance model applied to two Douglas-fir stands. *Water Resour. Res.* **17**: 1651-1656.
- WARING, R.H., and FRANKLIN, J.F. 1979. Evergreen coniferous forests of the Pacific Northwest. *Science (Washington, D.C.)*, **204**: 1380-1386.
- WARRACK, G., and JOERGENSEN, C. 1950. Precision measurement of Radial growth and daily radial fluctuations in Douglas-fir. *For. Chron.* **26**: 52-66.