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A height increment equation for young ponderosa pine plantations using precipitation and soil factors

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Abstract

A height increment equation was used to determine the effects of site quality and competing herbaceous vegetation on the development of ponderosa pine seedlings (*Pinus ponderosa* var. scopulorum Engelm.). Study areas were established in 36 plantations across northwest and west-central Montana on Champion International Corporation's timberland (currently owned by Plum Creek Timber Company). Site quality indices used in the equation were available water index (available water capacity multiplied by the natural logarithm of annual precipitation) and site index (SI) of the previous stand. Three-year height increment was modeled as a function of tree size, vigor, and competition by using available water index (AWI) and SI separately as site quality indicators in the same equation form. Comparison of the two equations suggest that soil factors in combination with precipitation data may be a useful alternative to traditional tree-based site quality indices in predicting height increment of young stands where site index is not known or is poorly estimated. Published by Elsevier Science B.V.

Keywords: Height growth; Western Montana; Site classification; *Pinus ponderosa*

1. Introduction

For a model to adequately characterize tree growth, it must include some measure of site quality, because site quality determines potential site productivity (Spurr and Barnes, 1980). In western forests, site quality has been primarily expressed by site index (SI) (Tesch, 1981). Site classification based on SI is not always accurate, due to harvesting, fire, disease, insect, or other disturbance, that may result in irregular stands (Myers and Van Deusen, 1960; McLeod and Running, 1988).

Additionally, estimating site index in very young stands is a persistent problem. The estimation of site index at a base age of 50 or 100 for seedlings is imprecise (Myers and Van Deusen, 1960; Brown and Loewenstein, 1978; Monserud, 1984). Furthermore, site index of the previous stand or an adjacent stand may not be a reliable choice. Adjacent stands may have a different site index. Furthermore, site index for a planted stand may not be the same as the previous stand because of genetic differences, species composition changes, or treatments applied to enhance growth and development of young stands (Fisher, 1984; Monserud, 1984; Powers, 1987).

Given the dilemma faced by many researchers regarding the best method to characterize site in young stands, Ford (1983) and Stone (1984) concluded that what is needed is a soil-based measurement of site quality that not only captures present productivity, but also responds to future management activities. When

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soil series or other mapping methods have been used as estimators of site quality, correlations have been weak (Farnsworth and Leaf, 1965; Van Lear and Hosner, 1967; Shetron, 1972). Relying on the ideas developed by Carmean (1975) and Stone (1984), Henderson et al. (1990) concluded that an approach integrating 'effective properties' of the entire rooting zone is needed to produce a measure of site productive potential.

Alternatively, soil factors and precipitation, which are based on permanent empirical features of site, have also been used separately or in combination as an indicator of site quality (Myers and Van Deusen, 1960; Brown and Loewenstein, 1978; McLeod and Running, 1988; Uzoh, 1992; Milner et al., 1996; Wensel and Turnblom, 1998). Available water capacity (AWC) is an estimate of the soil's capacity to store and hold water. Available water capacity in the soil is the amount of water the soil potentially can hold. By definition, it is the difference between soil water content at field capacity and the wilting coefficient (Peters, 1965; Jenny, 1980). AWC is a tree-independent indicator of site quality that directly integrates soil texture, soil depth, bulk density, and soil coarse fragment content characteristics into one quantity while indirectly expressing other site and biological factors. AWC indirectly influences photosynthesis rate, carbon allocation, and nutrient cycling by directly influencing site water balance (Zheng et al., 1996).

Properties that affect water-supply capacity to plants have consistently shown promise for predicting height growth (Ike and Huppuch, 1968), because high soil AWC indicates a site where maximum tree growth potential may be achieved (Gilmore et al., 1968). In moisture limiting environments, the presence or absence of readily available soil moisture in the rooting medium is one of the most important factors in determining a plant's success or failure (McMinn, 1952; Daubenmire, 1968a).

This study incorporates soil attributes and precipitation as proxys for site index to develop a 3-year height increment equation for use where site index is not known or is poorly estimated in newly established plantations of ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.). It is aimed at practicing foresters faced with the problem of predicting tree growth when suitable site trees are absent.

2. Methods

2.1. Study area and sampling design

This study began in the summer of 1987. Thirty-six plantations ranging in size from 5.7 to 14.6 ha (14–36 acres) were located in western Montana on Champion International Corporation's timberland (Fig. 1) (currently owned by Plum Creek Timber). Reforestation reports and plantation information from 1980 to 1986 for all Champion lands were accessed. From these reports, those plantations that had been clearcut and planted with mainly ponderosa pine were selected.

The plantations were selected with the aim of filling the cells of a 3×3×3 sampling matrix of precipitation, elevation, and age — each divided into Low, Medium, and High levels: for elevation classes (Low=610–1036 m, Medium=1067–1494 m; High=1524–2012 m), for precipitation classes (Low=387.4 mm, Medium=761.12 mm, High >1140 mm), and for age classes (Low=3–4 years, Medium=5–6 years, High=7–10 years). However, all cells were not filled (see Table 1), because of the silvical characteristics of ponderosa pine and the lack of plantations that could fill certain cells.

Ponderosa pine seedlings were measured in the summers of 1987, 1989, and 1990 for seedling height, live crown length, crown width, and diameter at 15.24 cm (0.5 ft) above the mean ground line. The percent cover of herbaceous vegetation (grasses, sedges, forbs, and shrubs) was estimated at the same time by summing vertical shadows that were cast by grass blades, leaves, and stems of individual species expressed as a percentage of ground surface (Dauben-

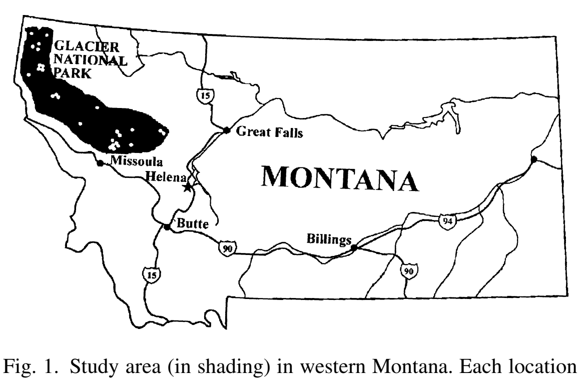

Fig. 1. Study area (in shading) in western Montana. Each location may have more than one plantation.

Table 1
The matrix of plantation selection showing number of plantations per cell (and individual tree height range in meters)[a]

	Precipitation					
	High		Medium		Low	
	No./cell	Range of tree height (m)	No./cell	Range of tree height (m)	No./cell	Range of tree height (m)
Low elevation						
Low age	0		3	0.24–1.31	2	0.24–0.64
Medium age	1	0.73–1.92	1	0.61–1.74	2	0.64–1.68
High age	0		2	1.25–3.48	2	1.01–2.38
Medium elevation						
Low age	1	0.61–1.59	1	0.24–0.76	0	
Medium age	0		2	0.70–1.52	3	0.48–1.56
High age	0		0		5	0.48–2.99
High elevation						
Low age	0		1	0.31–0.73	3	0.24–1.28
Medium age	0		2	0.48–1.71	1	0.37–0.85
High age	0		1	0.76–1.89	3	0.40–1.77

[a] For elevation classes (Low=610–1036 m, Medium=1067–1494 m; High=1524–2012 m), for precipitation classes (Low=380–740 mm, Medium=760–1120 mm, High >1140 mm), and for age classes (Low=3–4 years, Medium=5–6 years, High=7–10 years).

mire, 1968b). The radius of the area measured around each seedling/sapling for competing vegetation was between 1 and 1.5 m, depending on plantation age and tree size: for trees taller than 1 m in height, the radius of the area measured was 1.5 m, and for trees less than or equal to 1 m in height, the radius of the area measured was 1 m.

At each plantation, the sampling point center was located at random near the middle of the plantation. Sampling within a plantation was carried out in a spiral with ever-increasing radius from the sampling point center. Sampling continued until the cells of a 3×3 sampling matrix were filled with at least two trees. The sampling matrix consisted of crown ratio (ratio of crown length to tree height) and vegetation cover, each divided into Low, Medium, and High levels, with at least two replications (trees) per cell. For crown ratio, High >0.75, Medium=0.75–0.5, Low <0.5. For competing herbaceous vegetation cover, High >55%, Medium=55–35%, and Low <35%.

Grasses were the dominant competing herbaceous vegetation in the plantations. The grass component included bluebunch wheatgrass (*Agropyron spicatum*), rough fescue (*Festuca scabrella*), Idaho fescue (*Festuca idahoensis*), pinegrass (*Calamagrostis rubescense*), elk sedge (*Carex geyerii*), and cheatgrass (*Bromus tectorum*). However, the following forb and shrub species — beargrass (*Xerophyllum tenax*), ninebark (*Physocarpus malvaceus*), creeping holly grape (*Berberis repens*), snowberry (*Symphoricarpos albus*), twinflower (*Linnaea borealis*), kinnickinnick (*Arctostaphylos uva-ursi*), white spirea (*Spirea betulafolia*), menziesia (*Menziesia ferruginea*), thinleaf huckleberry (*Vaccinium globulare*), and ceanothus (*Ceanothus velutinus*) — were sparsely scattered across some of the plantations.

The granular form of the herbicide Pronone (2.24 kg active ingredient per hectare) was used for release treatment because it is not damaging to ponderosa pine, and it readily penetrates through the grasses, forbs, sedges, and shrubs to the ground. The herbicide was applied by spot application as a release treatment in the fall of 1987. Within the sampling matrix of crown ratio and vegetation cover, one of the paired trees in the corner and center cells was selected at random and treated (Box and Draper, 1987). Seedling growth was monitored for 3 years from 1988 to 1990. Data summary statistics are presented in Table 2.

2.2. Determination of available water capacity

To obtain representative soil data at each plantation, certain precautions were observed in locating soil pits.

Table 2
Summary statistics for data used to develop Eq. (6)

Variables	N	Minimum	Maximum	Mean	Std. Deviation
Height increment (m)	501	0.122	1.585	0.844	0.306
Initial height (m)	501	0.240	4.990	1.229	0.938
Crown ratio	501	0.353	0.979	0.717	0.126
Available water index (cm)	36	54.990	117.230	82.567	17.889
Site index (m)	36	15.240	33.528	19.693	5.504
Available water capacity (cm)	36	13.500	26.400	19.210	3.562
Precipitation (cm)	36	45.720	152.400	74.735	21.387
Non-crop veg. Comp. Index (NCCI)	501	0.000	260.000	64.317	53.261
Percent cover	501	0.000	100.000	55.367	39.396
Cover height (m)	501	0.000	0.793	0.249	0.185
Basal area in larger HT (INT) (m^2)	501	0.000	174.694	14.902	19.205

Heaps, road-sides, ephemeral creeks, or any feature suggesting a non-representative condition were avoided. Beginning at the center of each plot configuration, a single soil pit in the area that was subjectively judged to be the best representative of the entire plantation was located. Soil pits were excavated at each site to the depth of the soil parent material and the soil profile was described (USDA, 1984).

Texture was determined by sieving the soil to 2 mm, adding water to the point of cohesion, and molding the fine fractions into specific shapes. The cohesive soil was rolled by hand in an attempt to mold it into a series of shapes that defined the textural class using Kimmins's (Kimmins, 1987) key. I chose this method, rather than a more refined method such as texture from particle size analysis, because I wanted a technique that could be used easily in the field. Each horizon in the profile was assigned to a textural class (sand, silty sand, sandy loam, silt loam, silt, silty clay loam, clay loam, and clay).

AWC figures were then generated by using standardized values for each textural class (USDA, 1984). The volumetric AWC for the horizon was adjusted (multiplied) by the horizon depth and reduced by horizon coarse fragment content to obtain the AWC estimate for the horizon. Thus, AWC of each soil profile was obtained by summation of the available water capacity of each horizon in the profile:

$$\mathrm{TAWC} = \sum_{i=1}^{h} [\mathrm{AWCH}_i \times \mathrm{DEPTH}_i \times (1 - [(\%\mathrm{CFC}_i)/100])]$$

where TAWC is the total available water capacity in the profile (cm), AWCH_i the available water capacity (cm/cm) for the textural class of $\mathrm{horizon}_i$, DEPTH_i the depth to the nearest 1 cm of $\mathrm{horizon}_i$, $\%\mathrm{CFC}_i$ the percent coarse fragments by volume in the ith horizon to the nearest 5%, and h the number of horizons.

2.3. Site quality indices

Site quality indices used in the equation were available water index (cm) (AWI) and site index (SI) of the previous stand. Several transformations of annual precipitation and AWC were tested, but AWI gave the best result. AWI is available water capacity (AWC) multiplied by the natural logarithm of annual precipitation (cm). Annual precipitation data were obtained from isohyetal maps. The SI values were provided by Champion International Corporation. They are the SI values of the previous stand at the various plantations, based on 50-year breast height age (Martin, 1987).

3. Analysis

3.1. Theoretical formulation

In this study, the 3-year height increment of seedlings/saplings is modeled as a distance-independent model (Munro, 1974) in a composite equation framework as a function of tree size, site, vigor, and competition effects. The conceptual framework for the model is the positively skewed, unimodal height increment curve that is typical of tree growth processes (Wykoff, 1990). Theoretically, height increment increases to a maximum early in the life history of a tree and then gradually decreases, approaching zero as the tree matures. On a better site, all other things being equal, a tree of a given size is expected to attain a larger increment. Consequently, a tree with a healthy long crown is expected to attain a larger height increment than a tree with poor or sparse crown.

3.2. The equation

Growth of the individual trees was thought to be affected by three groups of variables: (1) tree size and vigor effects; (2) site effects variables; and (3) competitive effects. The combination of the following predictor variables and the transformation of several of these variables were initially tested for predicting 3-year height increment:

1. Tree size and vigor effects
   - Total tree height
   - Live crown length
   - Ratio of live crown length to total tree height
   - Live crown width
2. Site effects variables
   - Available water capacity
   - Precipitation
   - Elevation
   - Slope and aspect
   - Site index of the previous stands
3. Competitive effects
   - Basal area in larger trees
   - (Basal area in larger trees)/(DBH of the subject tree)
   - Percent cover of competing non-crop vegetation
   - Height of the competing non-crop vegetation
   - Crown area in larger trees
   - (Crown area in larger trees)/(crown area of the subject tree)

The best subsets of predictor variables were defined as those which (1) came closest to meeting the assumptions of regression analysis, (2) minimized residual mean squared error and Mallows' C_p statistics (Hockings, 1976), with C_p close to the number of parameters, and (3) maximized the coefficient of determination (R^2). Of the best subsets, the one selected for the equation was chosen based on the following criteria:

- Inclusion of appropriate variables with proper signs on the coefficients from a biological standpoint
- Low multicollinearity of the predictor variables
- Residual plots

3.3. Tree size effects

A logarithmic transformation was used to linearize the model and to make parameter estimates obtainable by ordinary linear regression minimizing the sum of squares. The following equation provided the best fit:

$$\ln(\mathrm{HTINC}) = b_0 + b_1 \ln(\mathrm{IHT}) + b_2(\mathrm{IHT})^2 + \varepsilon \quad (1)$$

where ln (HTINC) is the value of the natural logarithm of 3-year seedling/saplings height increment in meters, ln (IHT) the value of the natural logarithm of initial height, $(\mathrm{IHT})^2$ the value of the square of initial height, b_0, b_1, b_2 the regression coefficients and ϵ a random error term assumed to have expected value of zero (0) and constant variance (σ^2). When ln (HTINC) is transformed to height increment and plotted against IHT, the resulting function exhibited the desired properties, which is a skewed unimodal shape of a typical increment function (Fig. 2). The inclusion of $(\mathrm{IHT})^2$ gave Eq. (1) its asymptotic approach to zero for large height while retaining the essential advantages of the equation (Fig. 2). Additionally, the intercept term, b_0, can be expanded to include other tree factors and site effects that

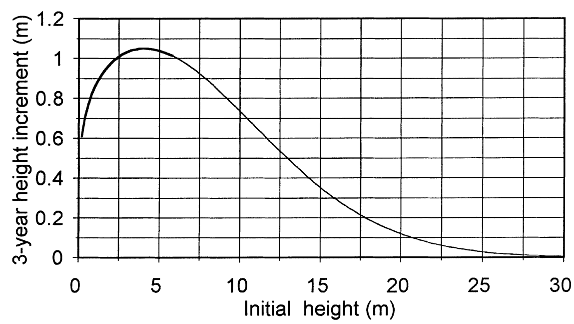

Fig. 2. Function plot of 3-year height increment by initial height using the coefficients derived for Eq. (1).

modify height increment while still retaining the basic relationship between tree size and growth (Wykoff, 1990).

3.4. Site effects variables

Three-year height increment was modeled as a function of tree and competition factors by using AWI and SI separately in the same equation form as site productivity indicators. The site quality indicator term is represented as:

$$\mathrm{SITE} = b_3\mathrm{SF} \qquad (2)$$

where SF is site quality indicator such as AWI or SI.

In addition to AWI or SI effects, other geoclimatic variation may remain. As a result, slope (SL) and aspect (ASP) terms can help in refining the overall site effect. Slope and aspect are included using Stage's (Stage, 1976) transformation. The combined effects of slope and aspect is represented by SA:

$$\mathrm{SA} = b_4\mathrm{SL}[\sin(\mathrm{ASP})] + b_5\mathrm{SL}[\cos(\mathrm{ASP})] \qquad (3)$$

3.5. Tree vigor

Crown ratio (CR) indicates the proportion of the tree stem which has branches with live foliage. CR is an indication of the photosynthetic capacity of a tree, and thus is an expression of tree vigor (TV). The vigor term is represented by CR as follows:

$$\mathrm{TV} = b_6\mathrm{CR} \qquad (4)$$

3.6. Competitive effects

The most important factor affecting conifer regeneration in the inland Northwest is competition from non-crop vegetation (Miller, 1986a). The non-crop vegetation competition index (NCCI) was calculated by multiplying percent cover of competing non-crop vegetation by cover height of the competing non-crop vegetation. Besides the competition effects of non-crop vegetation, the seedling/sapling height increment is also influenced by competition from other conifers within the plot. This inter-tree competition (ITC) effect was calculated using basal area in larger trees divided by the diameter of the subject tree using diameter measured at 15.24 cm (0.5 ft) above ground level. The competitive effects (CE) term is represented by NCCI and ITC:

$$\mathrm{CE} = b_7\mathrm{NCCI} + b_8\mathrm{ITC} \qquad (5)$$

ITC has been used as a tree-position variable in equations for predicting growth because it describes a tree's position in relation to all trees measured in a plot or stand (Dolph, 1984; Ritchie and Hann, 1985; Wykoff, 1986). Therefore, the largest diameter tree in a plot would have an ITC value of zero, while the smallest diameter tree in the plot would have an ITC value near the plot's total basal area (as measured at 15 cm).

4. Results

The following equation provided the best relationship between 3-year height growth of individual ponderosa pine trees, and (1) tree size and vigor effects, (2) site effects variables, and (3) competitive effects:

$$\begin{aligned} E[\ln(\mathrm{HTINC})] &= b_0 + b_1\ln(\mathrm{IHT}) + b_2(\mathrm{IHT})^2 + b_3\mathrm{SF} \\ &+ b_4\mathrm{SL}[\sin(\mathrm{ASP})] + b_5\mathrm{SL}[\cos(\mathrm{ASP})] + b_6\mathrm{CR} \\ &+ b_7\mathrm{NCCI} + b_8\mathrm{ITC} \end{aligned} \qquad (6)$$

where $E[\ln(\mathrm{HTINC})]$ is the expected value of the natural logarithm of 3-year seedling/saplings height increment (m), IHT the initial seedling/sapling height (m), SF the site factor such as AWI or SI of the previous stand, SL the average slope percent for the plantation, ASP the average aspect for the plantation (radians), CR the ratio of live crown length to total tree height, NCCI the non-crop vegetation competition index, ITC the (basal area in larger trees m^2)/(DBH of the subject tree cm) and b_i the estimated regression coefficients, i=0, 1, ..., 8 (see Tables 3 and 4).

The resulting statistics of the final model (Eq. (6)), indicate that all the slope coefficients were different from zero ($p<0.05$; Tables 3 and 4) with the exception of the coefficient associated with the square of initial height. The variable was not excluded from the equation because it made the model asymptotic to zero for larger height without adversely affecting the essential advantages of the model and eliminated the need to impose an arbitrary maximum height (Wykoff, 1990). Although the equation has many variables, each repre-

Table 3
Equation parameter estimates for Eq. (6) using available water index (AWI) as an indicator of site productive potential (R^2=0.338, standard error of estimate=0.349 (m), N=501)

Parameters	Estimate	95% Confidence interval			
		Standard error	Tolerance[a]	t-Statistic	p (two-tailed)
b_0	−1.408339	0.158996	–	−9.24074	0.00000
b_1	0.076485	0.040661	0.334008	2.51033	0.01238
b_2	−0.002510	0.006148	0.378245	−0.50217	0.61577
b_3	0.008476	0.000973	0.803553	8.65504	0.00000
b_4	0.004958	0.001154	0.960893	4.19877	0.00002
b_5	0.000438	0.001119	0.849595	0.43732	0.66207
b_6	0.863028	0.149165	0.687100	5.50925	0.00000
b_7	−0.002778	0.000995	0.933080	−2.96617	0.00503
b_8	−0.002808	0.000884	0.845196	−3.10213	0.00157

[a] Tolerance is 1 minus the multiple correlation between a predictor and the remaining predictors in the model. Values of tolerance near zero indicate that some predictors are highly intercorrelated.

sents an important component of tree growth. The regression of the 3-year height increment using a logarithmic transformation indicated R^2 values comparable with those found in other height growth studies where the same transformation was applied (Stage, 1975; Hasenauer and Monserud, 1997). The standard error of the estimate and R^2 when AWI was used in Eq. (6) were 0.349 (m) and 0.338, respectively. When SI was used, the standard error of the estimate and R^2 were 0.367 (m) and 0.268, respectively.

The increment attained by an individual tree is also dependent on its competitive status relative to neighboring trees. As a result, relative size is tied to plot density. Consequently, the coefficient of ITC is negative, indicating a competition modifier that would reduce height growth rates relative to a tree's competitive status. However, NCCI had more effect on seedling/sapling growth than ITC as shown by the t-statistics of their coefficients (Tables 3 and 4).

The logarithmic-bias correction to the intercept term (Flewelling and Pienaar, 1981) was estimated by adding half of the mean squared error to the intercept term (Baskerville, 1972). Flewelling and Pienaar (1981) suggested that for degrees of freedom >30 and S^2<0.5 the correction of $1/2S^2$ is usually adequate. Since the mean squared errors of the standard error estimates presented in Tables 3 and 4 are both <0.5 and the sample size is >30, Baskerville's

Table 4
Equation parameter estimates for Eq. (6) using site index of the previous stand as an indicator of site productive potential (R^2=0.268, standard error of estimate=0.367 (m), N=501)

Parameters	Estimate	95% Confidence interval			
		Standard error	Tolerance[a]	t-Statistic	p (two-tailed)
b_0	−0.850720	0.148357	–	−6.18821	0.00000
b_1	0.136602	0.042014	0.345416	3.25132	0.00123
b_2	−0.003643	0.006489	0.374865	−0.56140	0.57478
b_3	0.015318	0.003240	0.845134	4.72758	0.00000
b_4	0.004422	0.001252	0.902159	3.53196	0.00045
b_5	0.004089	0.001115	0.944305	3.66725	0.00027
b_6	0.686844	0.154719	0.705157	4.43930	0.00001
b_7	−0.003229	0.001043	0.936827	−3.09483	0.00208
b_8	−0.002578	0.000943	0.8186436	−2.73240	0.00651

[a] Tolerance is 1 minus the multiple correlation between a predictor and the remaining predictors in the model. Values of tolerance near zero indicate that some predictors are highly intercorrelated.

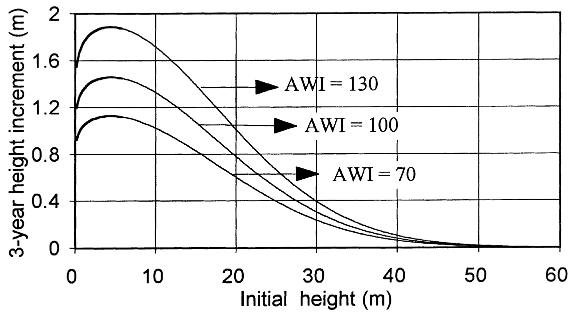

Fig. 3. Plot of 3-year height increment by initial height and available water index (AWI) projected beyond the database using the coefficients in Table 2.

correction should be a close approximation to the true logarithmic bias for the regression equation presented (Eq. (6)). Therefore, Baskerville's method was used for the logarithmic bias correction in Eq. (6).

Meanwhile, because the trees were still in the seedling and sapling stages, there were no differences between the plots of the resulting statistics (Tables 3 and 4) of the 3-year height increment using either measure of site quality indicators plotted against initial height and levels of AWI or SI. Consequently, Figs. 3 and 4 represent the projection of the function plots beyond the database, so that a better comparison of the resulting curves can be made.

Both plots (Figs. 3 and 4) have a maximum. However, it is evident that the rate of approach to zero for large height is moderate for Fig. 3 while the approach to zero in Fig. 4 is fast. Both figures are projections beyond the database; nevertheless, they show how the

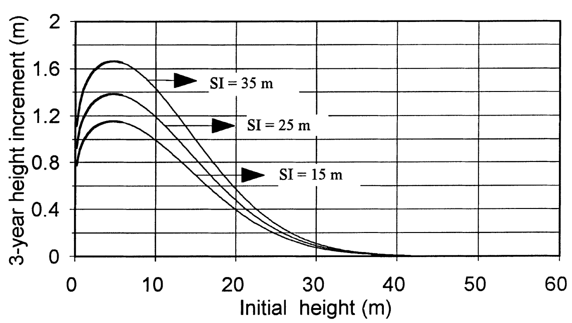

Fig. 4. Plot of 3-year height increment by initial height and site index (SI) projected beyond the database using the coefficients in Table 3.

resulting models extrapolate. Additionally, when extrapolated beyond the data set, the site index driven function did not come close to the actual entered height for higher values of site index. Furthermore, as shown in Tables 3 and 4, there is a difference between AWI and SI when each was used separately in Eq. (6) as site quality indicators. The coefficient of determination (R^2) was 0.338 and 0.268 for AWI and SI, respectively.

5. Discussion

The performance of AWI as a substitute index of site quality is not surprising because a review of the literature finds that soil properties consistently indicate site potential (Myers and Van Deusen, 1960; Brown and Loewenstein, 1978; McLeod and Running, 1988; Uzoh, 1992; Milner et al., 1996; Zheng et al., 1996). This study suggests that AWI, constructed from AWC for the entire rooting zone combined with precipitation, may be a good predictor of seedling/sapling height increment. AWC is a single variable that unites many soil variables, removing multicollinearity. For instance, AWC is a tree independent estimator of site quality that directly integrates soil depth, bulk density, coarse fragment content (CFC), and texture into one entity. Soil depth, bulk density, texture, and CFC define the physical properties of a soil that affect its ability to hold water.

AWC is indirectly related to soil nutrient capacity (i.e., cation exchange capacity, CEC), topography, and biological factors. Both AWC and CEC are, in part, surface area phenomena of soil particles related to soil texture. Not only do both AWC and CEC share a common physical origin, their values are roughly proportional (i.e. generally, a clay soil tends to have a high AWC and CEC, while a sandy soil has a low AWC and CEC) (Brady, 1990): the fine textured soils have both a greater surface area per unit volume exposed by their colloids (increasing CEC), and greater total micro-pore-porosity (affecting AWC).

Topographically, AWC also indirectly mirrors the effects of aspect and slope (Montagne et al., 1982). Whether by affecting infiltration or evaporation dynamics, or promoting soil development (and therefore soil depth, volume, and AWC), slope and aspect are site factors that affect AWC. Less biological growth occurs on southern aspects because this aspect receives more solar energy, has higher soil temperatures, and less available soil moisture due to evapotranspiration. These effects comparatively inhibits biogenic soil development on southern slopes. On average, northern aspects have deeper soil, more snow accumulation, more soil moisture, more soil organic matter, and higher fertility levels than southern aspects; therefore, they have higher AWC. Furthermore, slope steepness influences soil depth. Generally, steep slopes have shallow soils from solifluxion and colluviation, while gentle slopes have less movement and generally deeper soils. Consequently, by affecting soil depth, gentle slopes tend to have higher available water capacities than steeper slopes.

In addition to environmental factors such as nutrient capacity and topography, AWC also indirectly reflects biological factors impacting growth, such as root distribution (Henderson et al., 1990). Thus, by direct and indirect means, AWC is able to capture the influence of many site factors on seedling growth.

The success of this study in using AWI to model tree growth can also be attributed to several methods. First, soil pits were dug at each site to identify each site within the natural variability of AWC, which is not possible when using Soil Conservation Service (SCS) soil type averages. In addition, extensive soil pits of at least 1.5 m×1.5 m in dimension were dug, rather than resorting to augering, road-cuts, or other easier, less accurate means. Next, the depth of soil and root zone were clearly visible, increasing accuracy of measurement, and the volumetric percent of coarse fragments were precisely estimated.

Nevertheless, AWI has the following disadvantages: (1) one or more soil pits must be dug at each plantation depending on soil variability; (2) soil pits in rocky soil are difficult to dig; (3) consultation with a soil scientist may be necessary; (4) some soils are deep, and one may need to dig up to 2 m before reaching the parent material; and (5) generally, measurement of AWI is a time consuming and costly process. The two major advantages of AWI are that the precipitation data is easy to obtain from isohyetal maps, and if there is no major soil disturbance, AWC values remains the same for many years. In comparison, SI has the following disadvantages: (1) the stand may not be sufficiently old to obtain an accurate measure of SI; (2) if the stand has been high-graded, current overstory trees were not always dominant; (3) the stand may be irregular due to natural catastrophic events such as snow, wind, fire, insects, and ice storm; and (4) true site quality trees may be unavailable (Hann, 1998). The major advantage of SI is that it may be measured quickly and easily, at much less cost than AWI.

Although precipitation has been used to classify site (Yeh, 1997; Wensel and Turnblom, 1998), precipitation by itself did not provide an adequate indicator of site productive potential in this study. Nor did AWC by itself. In combination with precipitation, however, available water capacity provided a more complete description of site quality. Precipitation makes available water capacity a meaningful measure of site quality because it is the most important component of site variability in the hydrologic cycle (Kozlowski, 1982; Fetter, 1988). Although the entire hydrological cycle (such as inputs and outputs from lateral movement or percolation) was not modeled, it was assumed that precipitation was sufficient for making AWC a meaningful indicator of site quality. For example, two sites with identical AWC values will differ in quality depending on the amount of precipitation they receive. A soil with a high AWC cannot support tree growth if precipitation is limiting. On the other hand, 1 m of rain per year will mean less to tree growth if the soil does not have a sufficient AWC to hold that precipitation.

Therefore, the use of AWC in combination with precipitation data in building tree growth models may provide solutions to broader site index related problems in moisture-limiting environments for young stands. AWC combined with precipitation is not only a good predictor of height increment in young stands, it also provides an empirical method for a relatively static, soil-based standard of site comparison.

6. Conclusions

Henderson et al. (1990) asked the question, "Can measurable soil properties be integrated into a framework for characterizing forest productivity?" Similar to the performance of SI, soil and precipitation based equation developed in this study appears to be good proxys for site index in modeling ponderosa pine seedlings/saplings height growth. This demonstrates that soil factors in combination with precipitation may be a useful alternative when predicting height growth in young stands where site index is not known or is poorly estimated. Although there is much research to be done, we should strive to find other options for expressing site quality in young stands where site index is not known or is poorly estimated.

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