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Examining soil parent material influence over Douglas-fir stem growth response to fertilization: Taking advantage of information from spatiotemporally distributed experiments

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A B S T R A C T

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in the Inland Northwest region of the USA are nitrogen (N) deficient; however stem growth responses to N fertilizers are unpredictable, which may be due to poor accounting of other limiting nutrients. Screening trial experiments, including potassium (K), sulfur (S), and boron (B) multiple nutrient treatments, have been conducted to learn about Douglas-fir nutritional status and fertilizer growth response. The data from the screening trial experiments were compiled to test whether the soil parent materials of the region could be used to predict nutritional status. Estimating effects of fertilizers and soil parent materials on Douglas-fir growth from compilations of such experiments, however, poses challenges and opportunity; experiments clustered in time and space introduce latent variables that drive between-site variation. We used a two-stage modeling approach to efficiently take advantage of the information in these data. First, we employed a mixed model approach to test the primary hypothesis of soil parent material influence upon stem growth response to fertilizer. As the second-stage to the analysis, the predicted random effects estimated from the mixed model were used as a response variable to test how strongly precipitation drives between-site variation. As expected, including the random site effect significantly improved the model fit of the growth model (Λ = 436.5, P < 0.0001). The full mixed model accounted for 85% of the variation in the growth data (R^2 = 0.85) and revealed an interaction between fertilizer treatment and soil parent material class (P = 0.0179). Post hoc analysis suggested that Douglas-fir growing on loessal soils are not constrained by K, S, or B, but no general consistency was apparent with tephra or underlying geology. The second stage modeling suggested that winter precipitation explains variation in predicted random site effects (r^2 = 0.23), and hence the growth difference, better than total precipitation. Also, the annual lag precipitation explains variation in predicted random effects comparably well (r^2 = 0.22).

1. Introduction

In the Northwestern United States, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) are consistently nitrogen (N) deficient (Garrison et al., 2000; Moore et al., 1991, 2004); however stem growth response to N fertilizer additions are not consistent (Garrison et al., 2000; Shafii et al., 1990; Shen et al., 2000). To address the problem, workers have expanded focus to include examination of other nutrient limitations, including potassium (K), sulfur (S), and boron (B), that have sometimes explained the lack of growth enhancement to N-only fertilizer (Blake et al., 1990; Moore et al., 1991; Turner et al., 1979). However, prediction of nutritional status is still difficult without fertilization experiments on particular sites, and as a consequence determining the nutritional status of Douglas-fir remains difficult.

In light of the difficulty, the Intermountain Forest Tree Nutrition Cooperative (IFTNC) at the University of Idaho began conducting fertilizer screening experiments across the landscape as an efficient way to collect information on Douglas-fir nutrient status for various soil parent material types (Garrison-Johnston et al., 2007). In the region, the soil parent materials under sites are typically combinations of hard-rock, underlying geologic material and surficially deposited materials. The surficially deposited materials in the region are volcanic ash (tephra) from the cataclysmic eruption of Mount Mazama and eolian loess originated from the Columbia Basin glacial deposits (McDaniel and Hipple, 2010). As

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a result of these screening experiments, a data archive has grown containing a picture of Douglas-fir nutritional status across the region, time, and soil parent materials. Specifically, these data contain information on our primary interest of whether soil parent material can be used as an indicator of nutrient status, as well as the effects of the latent drivers of between-site variability.

In this study, we analyzed the archived data. The objectives of the study were to (1) unmask the average effects of N and multi-nutrient fertilizer and soil parent material on Douglas-fir stem growth, (2) interpret those effects, and (3) model the effects of the latent drivers of between-site variation in this model. To complete the objectives, we employed a two-stage modeling approach. First, the fertilizer–soil parent material interaction is examined in a stem growth model, both with and without a random intercept for site. Secondly, the predicted random effects are used as a response variable to explore drivers of between-site variability.

2. Methods

2.1. Sites

The dataset used in this study was compiled from 33 individual-tree, fertilizer screening trial experiments conducted between 1999 and 2005 by the IFTNC (Garrison et al., 2004, 2005a,b; Kimsey et al., 2000, 2007). The screening trials (also referred to as installations) were all located in the Inland Northwest region of the United States, on sites in northeast and central Washington, northeast Oregon and northern Idaho. Each installation consisted of 15 Rocky Mountain, or Inland, Douglas-fir selected for fertilization and monitoring. The trees were selected such that there were 10 m between nearest neighbors. The spacing was chosen to prevent cross-contamination of fertilizer treatments. Visual inspections of the trees helped prevent inclusion of diseased trees in the experiments. Before the end of the study, one tree in four of the screening trials underwent mortality; these trees were excluded from the study.

The sites themselves were selected based on certain common features as part of the IFTNC screening trial design to compass a variety of soil parent material classes common to the region. For the common features, none of the stands on the sites were near canopy closure. All had a relative density index (Drew and Flewelling, 1979) less than 20%. Because the stands on the sites were all low in density, and had not reached crown closure, it was assumed that trees were free to grow without competition. The initial tree heights across sites ranged between 1.1 and 12.2 m tall. The sites fell in a narrow range of average expected soil moisture, as indicated by the moisture-defined habitat types (Daubenmire and Daubenmire, 1968), which were either a wetter grand fir type (Abies grandis Dougl ex D. Don (Lindl.)) or a western red cedar type (Thuja plicata Donn ex D. Don). All of the sites were well-suited for Douglas-fir.

The soil parent material of each site was usually a combination of older underlying geologic materials and the more recently deposited tephra and/or loess. The older underlying materials were classified into categories based on nutrient composition by an experienced, regional Idaho Geological Survey staff geologist at the University of Idaho. The soil parent material combinations were identified by using geologic maps to anticipate the older, underlying material, and examining the soil to a depth of 1.5 m. Soil profiles were examined by digging soil pits or taking soil core samples. The 1.5 m depth was chosen to account for materials in the Douglas-fir rooting zone. In no cases were the tephra and/or loess deposits >1.5 m thick. Consequently, we expected that the underlying geologic material always had an influence on the Douglas-fir rooting-zone. The tephra and loess surficial deposits were only considered part of the soil parent material when the material was at least 15 cm thick. The combination of underlying geologic and surficial deposit materials at each site resulted in nine general soil parent material categories (Table 1) that together describe >90% of the bedrock–surficial deposit combinations occurring in the Inland Northwest.

2.2. Fertilization

Within each installation, each tree received a fertilizer treatment. The fertilizer treatments were a non-fertilized control, a N-only fertilization, or a multi-nutrient blend. The fertilizer assigned to a tree was applied to a circular area by granular broadcast with a 3 m radius buffer beyond the crown of each tree. The rate of N and multi-nutrient blend differed somewhat among installations, depending on the original study objectives. Nitrogen was applied as urea CH_4N_2O–N at either 224 or 336 kg N ha^{-1}. The rate between N-only and multi-nutrient blend was consistent within each installation. Response differences between the N fertilizer rates are typically a fraction of the differences for either rate relative to the non-fertilized control (Moore et al., 1991), so we grouped the N fertilizations together for analysis. For the other nutrients in the multi-nutrient blend, there were several small differences among installations. One difference in the multi-nutrient blend was that K was excluded from some of the blends but present in others; however K has never influenced individual-tree growth in this region, even after N deficiencies are alleviated (Garrison et al., 2000). Potassium-free and K-containing blends were not mixed within a soil parent material class. Another difference in formulations was that copper (Cu) was included in some of the blends but not in others; however, Cu has since been discounted in importance to stem growth. Given that N-rates and K and Cu differences were not expected to influence stem growth in the design, the fertilizers were-reclassified into three categories, control (C), N-only (N), or multi-nutrient (M) (Table 2).

2.3. Measurements and study variables

To compute stem volume growth, tree measurements of height and diameter were taken for each tree in the study. The measurements were taken twice, once in fall at the time of installation establishment, and again in fall 2 years later. Stem volume growth for each tree was estimated using a regional, species-specific equation for Douglas-fir found in Wykoff et al. (1982). The average annual stem volume growth was then calculated as half of the difference between the estimated volumes at the two time points. Extending the equation from Wykoff et al. (1982) for each tree, average annual stem volume growth was calculated as:

$$\frac{dV}{dt} = \left(\frac{1}{2}\right)\left[\beta_0\left(d_2^2h_2 - d_0^2h_0\right) + \beta_1(d_2h_2 - d_0h_0)\right],$$

where β_0 = 0.001714 and β_1 = 0.003865 are parameters; d and h are the bole diameter and height at years zero and two. Diameters and

Table 1
Soil parent material classes in the database analyzed in this study, along with the corresponding numbers of sites.

Soil parent material classes	# Of sites
Basaltic	4
Basaltic with ash	4
Basaltic with ash and loess	2
Granitic with ash	5
Low-Ca metamorphic with ash	5
Low-Ca metamorphic with loess	1
Low-Ca metamorphic with ash and loess	3
Medium-Ca metamorphic with ash	7
Unconsolidated sediments with ash	2

Table 2
Fertilization rates and fertilizer reclassification scheme.

Nutrient addition rates of the fertilizers ($kg\ ha^{-1}$)					# Of sites	Reclassification
N	K	S	B	Cu		
0	0	0	0	0	33	Control
224	0	0	0	0	15	N-only
336	0	0	0	0	18	N-only
224	0	100	3.36	11.2	8	Multi-nutrient
224	190	100	3.36	11.2	3	Multi-nutrient
224	190	100	3.36	0	4	Multi-nutrient
336	190	100	3.36	0	18	Multi-nutrient

heights entered the equation in units of inches and feet, respectively. The predicted change in stem volume was in $ft^3\ yr^{-1}$, which was converted to $dm^3\ yr^{-1}$. The secondary analysis in this study was based on predicted random site effects estimated with the mixed model employed in the primary analysis. A similar approach was employed in Weiskittel et al. (2007). The other variables considered in the study were fertilizer, soil parent material, initial tree volume, and variables derived from spatiotemporally explicit precipitation data. The precipitation data were obtained as described below.

To take explicit advantage of the spatiotemporal information in the predicted random effects in the second stage of the analysis, we extracted predicted monthly precipitation across the landscape from the PRISM database (Prism Climate Group; http://prism.oregonstate.edu, obtained June 2010). There were 84 temporally static, spatially explicit predicted monthly precipitation layers from which precipitation data were connected to each of the sites. The task of extraction was automated using a specially tailored computer program written in the Python language (http://www.python.org) for work in ArcGIS. For each site, the monthly precipitation data temporally ranged from a 1-year lag until the final measurement. Eleven precipitation variables were derived as sums of monthly precipitation; the sums included total, seasonal, and lagged precipitation. The temporal ranges for the eleven variables are given in Fig. 1. All ArcGIS tasks were performed in version 9.3.1.

2.4. Statistical analysis

2.4.1. Stage 1

In the first stage of the analysis, two models were compared. Hypotheses were tested for significance of random site effects and the influence of soil parent material on Douglas-fir fertilizer response. The first step taken was to account for the relationship between stem growth and initial tree volume (after Wykoff, 1990). The univariate distributions of each had positive skew, as was anticipated, so the variables were subsequently transformed to the logarithmic scale. The logarithmic scale was chosen for transformation of the variables for two reasons: (1) it aligned with the theoretical basis in deterministic growth modeling (Zeide, 1993) and (2) the logarithmic transformation sufficiently improved the noise assumptions of the linear model.

After transformations, the two models were fit. First, we fit a linear fixed effects model with the dependent variables of log initial tree size and indicator variables for soil parent material, fertilizer and the fertilizer-soil parent material interaction terms. Next, the second model was fit with the same fixed effects part as the first model, but with the addition of a random intercept for the effect of site. The two models were parameterized by restricted maximum likelihood (REML), so that the effect of site could be tested for significance by the likelihood ratio test (Zuur et al., 2009, p. 133). Each model was fit separately using the MIXED procedure in the SAS/STAT® software with the Kenward–Rogers adjustment on the degrees of freedom. The fixed effects model can be expressed as:

$$\log\frac{dV}{dt} = intercept + \log V_0 + Fert + SPM + Fert \times SPM + \varepsilon,$$

where $\log\frac{dV}{dt}$ is the natural logarithm of stem growth, V_0 is the initial tree volume, *Fert* is fertilizer level, *SPM* is soil parent material, and ε is the residual error. The mixed effects model can be expressed the same way, but with the added random intercept for the effect of site represented by the *site* term.

$$\log\frac{dV}{dt} = intercept + \log V_0 + Fert + SPM + Fert \times SPM + site + \varepsilon$$

The likelihood ratio statistic used to test the significance of the random site effect was approximated as the difference in deviance between the mixed and fixed effects models. The likelihood ratio statistic and computation for the significance of the random effect of site can be expressed as:

$$\Lambda = D_F - D_0,$$

$$P\text{-}value = \frac{1}{2}\left[Prob(\chi_1^2 > \Lambda | no\ site\ effect)\right]$$

where D_F is the deviance, −2 REML log likelihood, of the full, mixed effects model, and D_0 is the deviance of the fixed effects model. Hypotheses of the tests of significance of fixed effects in each model were tested using Type II sum-of-squares. A generalized R^2 value for the mixed effects model was computed as:

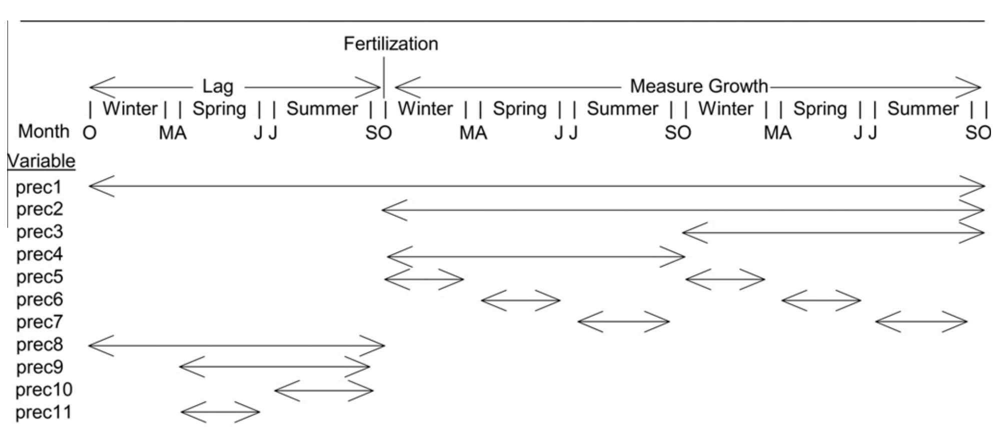

Fig. 1. Temporal spans over which PRISM predicted monthly precipitation (Daly et al., 1994) was summed within each of the screening trials in the study.

$$R^2 = 1 - \frac{D_F}{D_N},$$

where D_F and D_N are the deviances of the full mixed effects model and null model, respectively (Fox, 2008, p. 387). Also, a post hoc analysis on the fixed treatment groups in the mixed model was conducted via least-squares means. Significance was decided at $\alpha = 0.05$.

2.4.2. Stage 2

The second stage of the analysis examined the predicted random effects for the mixed model from stage one as a function of either a real-time precipitation group or lag-only precipitation. The univariate distribution of the predicted random effects was skewed, and given that no previous work or theory was instructive to the appropriate transformation, a Box-Cox power transformation approach was employed. The TRANSREG procedure was used to estimate the appropriate power transformation for each of the two groups separately. Also, two was added to the predicted random effects, so that zero, or the log transformation, could be included in the algorithm. The results from the SAS procedure indicated appropriate squaring of predicted random effects, so we squared the predicted random effects prior to fitting.

Next, model selection was conducted using the REG procedure. In the model selection, the number of independent variables allowed in the model was increased incrementally. Within each increment, the models were ranked by correlation coefficient (r^2 for simple linear regression and R^2 for multiple regression) and selection was instructed by minimum Akaike information criterion (AIC). Models were selected ad hoc based on validity, information content by AIC, and $\alpha = 0.05$ parameter significance.

3. Results

3.1. Growth response to fertilizer and soil parent material

The addition of the random effect for site significantly improved the fit of the model ($\Lambda = 436.5$, $P < 0.0001$), indicating that some latent variables were driving between-site differences. Moreover, adding the random site effect installation term improved the behavior of the residual errors in terms of homogeneity and reduced the model deviance (Fig. 2). The mixed effects model captured about 85% of the variability in stem growth ($R^2 = 1 - (199/1318.2) = 0.85$). Without the random term for site, the fertilizer-soil parent material interaction was not significant ($P = 0.6932$), but it was significant in the mixed effects model ($P = 0.0179$; Table 3).

A post hoc slice analysis suggested a significant fertilizer effect on four of the nine soil parent material classes, and means comparisons within the classes suggested three response patterns, a positive response to N but no additional boost with the multi-nutrient blend, no positive response to N-only but a positive response to the multi-nutrient blend, and no significant response to either fertilizer. The soil parent material classes on which there was no significant growth response to fertilizer are indicated with "ns" in Fig. 3. Douglas-fir on one of the nine classes, low-Ca meta-sedimentary rock with ash and loess, increased in stem growth if fertilized with N (C treatment < N treatment, $P = 0.0214$), but there was no additional gain with the multi-nutrient blend (Fig. 3e). Conversely, on the other three soil parent material classes in which there was a positive response, there was response over the control to the multi-nutrient blend, but not N-only. These occurred on the basaltic parent material (C treatment < M treatment, $P < 0.0001$; Fig. 3c), low-Ca meta-sedimentary rock with ash (C treatment < M treatment, $P = 0.0001$; Fig. 3f), and on medium-Ca meta-sedimentary rock with ash (C treatment < M treatment, $P = 0.0001$; Fig. 3h).

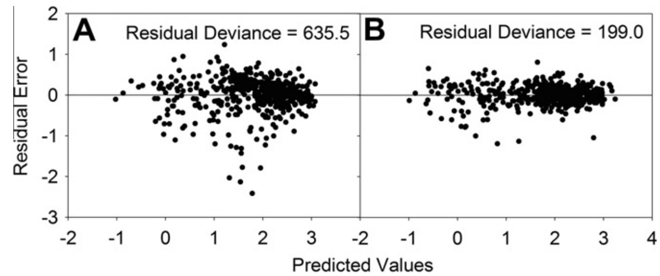

Fig. 2. Residual error by fitted values of the (A) fixed effects and (B) mixed effects models. The fixed effects model explained the logarithm of Douglas-fir volume growth by the logarithm of initial tree volume and categorical variables fertilizer, soil parent material class, and fertilizer–soil parent material interaction. The fertilizers levels were control, N-only fertilization, and a multi-nutrient blend of N, S, K, and B. Soil parent materials classes were derived as combinations of old, underlying geology and the newer surficially deposited tehpra and loess materials in the Inland Northwest, USA. The mixed effects model had the same fixed effects terms as the fixed effects model, but included an additional random effect to account for latent spatiotemporal drivers of between-site variation.

Table 3
Type II ANOVA results for the fixed effects in the mixed effects model. Log initial tree volume is the natural logarithm of initial tree volume.

	Numerator DF	Denominator DF	*P*-value
Fertilizer	2	439	<0.0001
Soil parent material	8	23.8	0.2063
Fertilizer × soil parent material	16	439	0.0179
Log initial tree volume	1	460	<0.0001

3.2. Site effects

The secondary analysis of the predicted random site effects yielded well competing models from the selection procedure for both groups of precipitation sums. Candidate models from the procedure on the two precipitation variable groups are given in Table 4. In the first group, winter precipitation during growth measurements (prec 5) was the best model. The model is depicted in Fig. 4. Total sum and total during growth measurement only precipitation groups (prec 1 and 2) closely competed with the winter-only consideration. Accounting for winter and summer precipitation added some explanatory power over the simple linear regression, but the parameter estimate for the summer term was not significant, possibly due to variance inflation (VIF = 7.5) from correlation between summer and winter precipitation. The lag-only precipitation variable group explained the predicted random effects just as well as the first group. Total sum lagged-only precipitation (prec 8) was consistently selected by the selection procedure (Table 4). The simple linear regression was chosen as best, and the model is depicted in Fig. 5. Similarly to first group of precipitation terms, the two term models in the lag-only group also yield insignificant parameter estimates.

4. Discussion

The main purpose of compiling the data collected from the screening trial experiments was to assess whether soil parent material classes could be used to determine Douglas-fir nutritional status across the landscape. The results of the analysis suggested that knowledge of the soil parent materials is informative. Without accounting for random site effects, however, there was no interaction between fertilizer and soil parent material. Nonetheless, finding the interaction with the inclusion of the random effect of site suggests that soil parent materials do determine nutritional status,

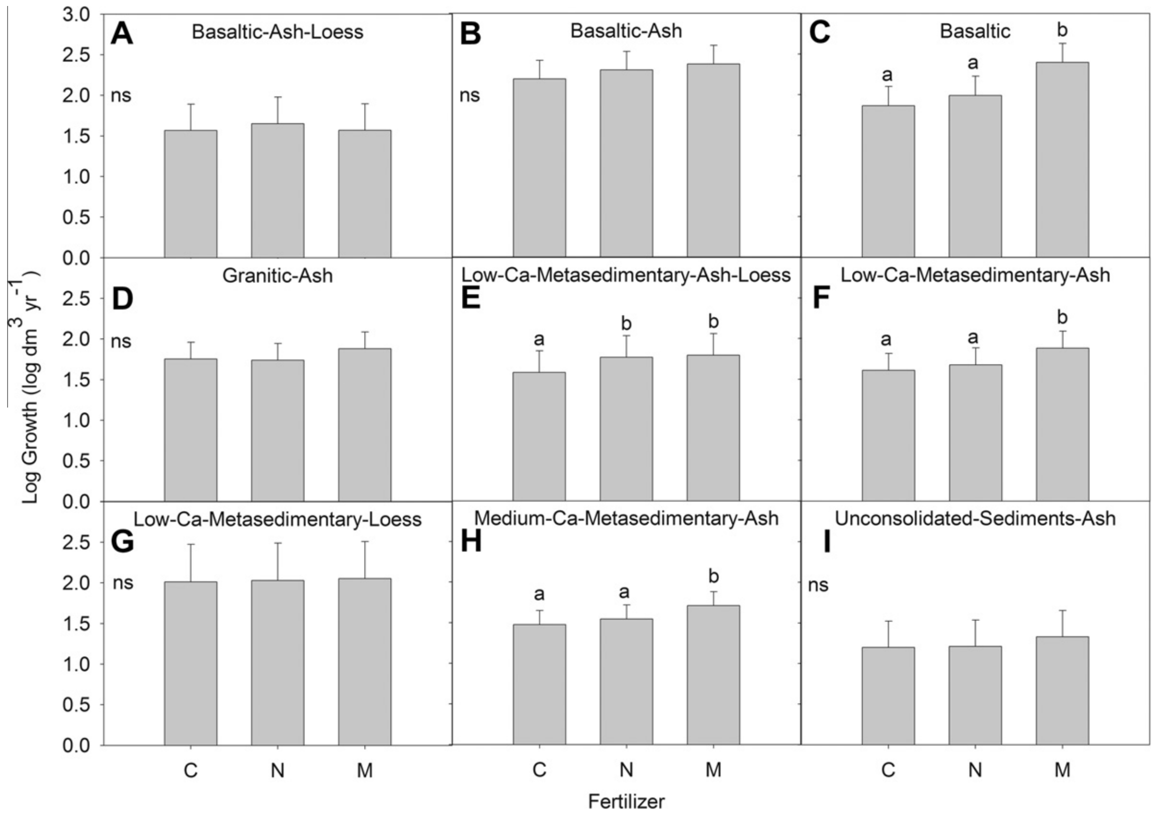

Fig. 3. Post hoc means comparisons of the fertilizer treatments within soil parent material classes. The natural logarithm of stem volume growth is on the *y*-axis. The "C" is for the unfertilized (control), "N" is for the N-only fertilized trees, and "M" is for trees that received the multi-nutrient blend fertilizer. Within panels, bars with different letters are significantly different. The ns indicates no significant differences. The error bars on each bar indicate ± standard errors.

Table 4
Model selection results for the models of predicted random effects. Selection was conducted separately for two groups of variables, precipitation, and precipitation only before fertilization. The precipitation variables (prec) are defined in Fig. 1.

Variables	AIC	r^2or R^2
prec5	12.7	0.23
prec1	13.2	0.22
prec2	13.9	0.20
prec4	15.7	0.15
prec1, prec7	12.9	0.27
prec2, prec5	12.9	0.27
prec5, prec7	13.4	0.26
prec8	13.2	0.22
prec9	18.5	0.08
prec8, prec9	13.7	0.25
prec8, prec10	14.2	0.24
prec8, prec11	14.9	0.22
prec9, prec11	20.5	0.08

but that knowledge of the materials by themselves is not likely to be a strong predictor of whether the trees are under a solely nutritional stem growth constraint.

The most general and implicative finding is that the Douglas-fir growing on soils formed from loess surficial deposits were not limited in stem growth by K, S, or B. This feature in the results is general across all the responses, but it is even more strongly supported by comparing the response patterns between the low-Ca meta-sedimentary rock with ash, with and without loess. Where loess was present, only N was required to enhance stem growth. The mechanism may be nutritional, soil pedologic, or a combination of the two. For instance, the loess sometimes still has a significant $CaCO_3$ component (McDaniel and Hipple, 2010), which easily weathers to release K and B (Kitano et al., 1978; Okumura and Kitano, 1986). Also, the loess soils have associated micas that weather directly to vermiculite (McDaniel and Hipple, 2010), which increases the capacity of the soil to hold plant available water and store nutrients through enhanced cation exchange

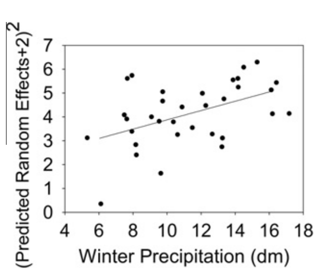

Fig. 4. Simple linear regression of predicted random effects on winter precipitation during each of the screening trials. The model can be expressed as $Y^2 = 1.94543 + 0.1947 * X + \varepsilon$. Other model details are given in Table 4.

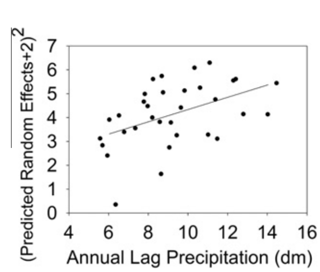

Fig. 5. Simple linear regression of predicted random effects on the total annual lag precipitation during each of the screening trials. The model can be expressed as $Y^2 = 1.77417 + 0.2570 * X + \varepsilon$. Other model details are given in Table 4.

capacity. The high capacity of the soil to store nutrients and water increases the potential of nutrient flux to the trees (Anderson, 1988), which in turn alleviates requirements for nutrients other than N to improve stem growth.

Conversely, the tephra and underlying geologic materials were not consistent determinants of nutritional status. For instance, fertilizer responses occurred in the presence of tephra, but not in all cases. The unpredictability of fertilizer response in the presence of tephra is reasonable given findings in the literature. Tephra is highly siliceous in composition, so is relatively low in major nutrients (McDaniel and Wilson, 2007; Sarna-Wojcicki et al., 1983); hence the other soil parent materials on a given site are important for tree nutrition in the presence of ash caps. Moreover, not only does the tephra not contribute substantially to the nutrient pool, it often induces a negative nutritional feedback on sites. Tephra-rich soils can render essential nutrients unavailable to trees through irreversible anion adsorption processes (Kimsey et al., 2011). Nutrient concentrations in the soil need to be at levels higher than some threshold value in order to attenuate irreversible adsorption, so it is not surprising that the status of soil nutrient availability could be inconsistent across sites with ash caps. For the influence of the underlying materials, the differing response patterns among the soil parent material combinations that include basaltic rock and low-Ca metasedimentary rock, for example, certainly imply that the underlying materials may not provide a consistent means to determine tree nutrient status, at least on those materials.

The second stage in the analysis was conducted simply to exploit the extra information in the data due to the hierarchical nature of the screening trial compilation. However, the analysis is certainly of interest to workers interested in Douglas-fir in the region, since explanation of the predicted random effects directly implies explanation of growth differences among sites. The predicted random site effects in the mixed model modify the growth intercept according to site to better account for fertilizer and soil parent material effects in the Douglas-fir population. This, in effect, modifies the mean growth response as a function of site.

The precipitation variables in this study were largely comparable in explanatory power of between-site differences in growth, albeit the explanatory power was not very remarkable. Even the best models accounted for less than 25% of the variation. Interestingly, however, when considering only winter precipitation during growth measurement (prec 5), the explanatory power of the models does comparably well to the other, longer sum variables. The finding aligns with the tendency for dry early winter seasons in which temperature is still adequate for growth, but the early winter is dry. The winter precipitation possibly has greater interannual variability than the other seasons and exerts greater influence over growth in the water limited late season. Some of our unpublished work suggests that stem growth is better in years when rainfall is unusually high in September and October. In addition, more snowmelt at the end of winter might be providing extra moisture in spring (Griesbauer et al., 2011). The lagged total annual precipitation predictor may have been important due to correlation with average total annual precipitation on sites, or some other mechanism such as facilitation of adequate nutrient storage within trees for use in the next growing season. Further research is needed to address the implied hypotheses.

5. Conclusions

In this study, individual-tree screening trial experiments were compiled to test whether soil parent materials could be used as an indicator of Douglas-fir nutritional status in the Inland Northwest region of the USA. Stem growth response to N-only and multi-nutrient blend fertilization differed according to soil parent material classes, indicating that soil parent materials do influence nutritional status, but the significance of the random site effects indicates marked site variability. Specifically, the results suggested that Douglas-fir growing on soils forming from the regional loess surficial deposits may not be limited in stem growth by K, S, or B. Conversely, underlying geology and regional tephra deposits were not consistent determinants of nutritional status. Hence, nutrient management on sites with loessal soils may not need as much attention in regards to K, S, and B as sites without loess.

In addition, by doing the data compilation, we were afforded the opportunity to explore latent drivers of between-site growth variation. A set of derived variables for precipitation before and during the experiments explained about 23% of the variation in the predicted random site effects, a proxy for differences between average stem growth and growth on particular sites. The importance of winter precipitation during the experiment suggested that rainy Octobers and early snow melts considerably boost stem growth. Total annual precipitation before and during the experiments also had explanatory power. Knowing that lagged annual precipitation can explain growth provides some insight into predicting growth in the following year.

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