The use of various soil and site variables for estimating growth response of Douglas-fir to multiple applications of urea and determining potential long-term effects on soil properties

Eric B. Sucre, Robert B. Harrison, Eric C. Turnblom, and David G. Briggs

Abstract: Estimating the growth response of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands after nitrogen (N) fertilization is difficult because of the high site variability present in the Pacific Northwest. Our objective was to determine how site and soil variables relate to stand response to repeat applications of 224 kg N·ha^{-1} as urea once every 4 years. The unstandardized residuals of two dependent variables (total cumulative volume and 4-year periodic annual increment, or PAI) were regressed against site and soil variables using stepwise regression. Data were stratified by three different stand density treatments: unaltered stand density (SD), one-half SD (SD/2), and one-quarter SD (SD/4). Both total cumulative volume and 4-year PAI after the second application of urea was significantly higher in the fertilized plots (p = 0.008; 0.009), whereas only total cumulative volume was significant after the third fertilizer application (p = 0.021). Thinning effects were highly significant (p < 0.001) for all three fertilizer applications. The strongest related stand, site, or soil variable to fertilization response existed between percent N at the 30–50 cm depth and total cumulative volume (R^2 = 0.833) for the SD/2 stand density management regime. Regression analysis showed that C, N, NH_4^+, and NO_3^- concentration data explained the most variation, while stand and site variables contributing the least. The results demonstrate that multiple applications of urea provide significant increases in total volume, but effects of successive applications diminish over time.

Résumé : Il est difficile d'évaluer la réaction en croissance de peuplements de douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) après une fertilisation azotée (N) à cause de la grande variabilité des stations du nord-ouest américain. Notre objectif était de déterminer comment les variables du sol et de la station étaient reliées à la réaction du peuplement à la suite d'applications répétées de 224 kg N·ha^{-1} sous forme d'urée à tous les quatre ans. Les résidus non standardisés de deux variables dépendantes (volume total cumulatif et accroissement annuel périodique (AAP) pendant une période de quatre ans) ont été mis en relation avec des variables de sol et de station à l'aide de la régression pas à pas. Les données ont été stratifiées selon trois traitements de la densité du peuplement : densité du peuplement non altérée (SD), 50 % de la densité du peuplement (SD/2) et 25 % de la densité du peuplement (SD/4). Le volume total cumulatif et l'AAP pendant une période de quatre ans étaient significativement plus élevés dans les parcelles fertilisées après la deuxième application d'urée (p = 0,008 et 0,009) alors que seul le volume total cumulatif était significativement plus élevé après la troisième application de fertilisant (p = 0,021). Les effets de l'éclaircie étaient très significatifs (p < 0,001) pour les trois applications de fertilisant. La relation la plus étroite entre une variable de peuplement, de station ou de sol et la réaction à la fertilisation était celle qui existait entre le pourcentage d'azote à une profondeur de 30 à 50 cm et le volume total cumulatif (R^2 = 0,833) dans le cas du régime d'aménagement de la densité du peuplement SD/2. Une analyse de régression a montré que la concentration en C, N, NH_4^+ et NO_3^- expliquait la plus grande partie de la variation alors que les variables du peuplement et de la station y contribuaient le moins. Les résultats démontrent que des applications multiples d'urée produisent des augmentations significatives du volume total, mais que les effets d'applications successives diminuent avec le temps.

[Traduit par la Rédaction]

Introduction

Accurately selecting forest stands that will respond to fertilization has always been a challenge for forest managers. This is largely due to soil resource heterogeneity and the amount of variability that exists between stands across large spatial scales. In the Pacific Northwest, nitrogen (N) availability is typically the most limiting factor restricting stand growth (Gessel et al. 1973). About 65 000 ha of forest land in the Pacific Northwest is annually fertilized with N to offset this limitation (Briggs and Trobaugh 2001). On average, volume growth of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) after N fertilization is enhanced in over 70% of Douglas-fir trials; however, the degree of response is highly variable across sites (Miller et al. 1986) and forest stands with similar site characteristics often respond differently (Peterson et al. 1984). The average duration of volume response for thinned Douglas-fir stands following a single

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application of nitrogenous fertilizer at a rate 224 kg N·ha^{-1} is approximately 8 years (Opalach et al. 1987; Omule 1990), and occasionally ≥10 years (Strader and Binkley 1989; Mitchell et al. 1996). On the other hand, nonthinned Douglas-fir stands have shown longer more continuous volume responses to fertilization for 12–14 years (Peterson and Heath 1986; Stegemoeller and Chappell 1991). Many Pacific Northwest Douglas-fir stands that initially respond to N fertilization continue to show significant volume responses with subsequent fertilizer applications (Chappell et al. 1991; Weetman et al. 1997).

Several studies have examined whether various stand, site, and soil variables can be used to predict Douglas-fir response to fertilization. For example, prefertilization foliar levels of inorganic sulphate (SO_4-S) (Turner et al. 1977, 1979, 1988; Carter et al. 1998) and N (Hopmans and Chappell 1994; Carter et al. 1998) have been used to predict fertilization response for Douglas-fir. For example, Turner et al. (1979) found that foliar levels of SO_4-S accurately predicted fertilization response for 17 out of 19 (90% accuracy) Douglas-fir stands, whereas only 12 of those responsive stands were identified (63%) when foliar N concentrations were used. However, Hopmans and Chappell (1994) found that 94% of the variation was explained when foliar N was used as a predictive variable for fertilization response. The use of foliar N and SO_4-S as surrogates for selecting sites as candidates for fertilization has varied, but in many instances they have explained a significant amount of the observed variation and are relatively inexpensive to measure (Turner et al. 1988; Hopmans and Chappell 1994). In addition to foliar chemistry being used as predictive variables, several soil chemical properties have shown merit, such as mineralizable N (Shumway and Atkinson 1978; Powers 1980; Radwan and Shumway 1984; Blake 1985), forest floor and mineral soil carbon (C)/N ratios (Peterson et al. 1984; Edmonds and Hsiang 1987), and exchangeable potassium (K^+) (Edmonds and Hsiang 1987). These studies reiterate the heterogeneous nature of forested ecosystems and how stand and soil properties identified as predictors for fertilization response may be site or regionally dependent.

Forest fertilization is an expensive and often risky venture because of this inability to accurately predict which sites and (or) stands will significantly respond to N fertilization. This uncertainty often generates a great deal of skepticism amongst many forest managers. All of the aforementioned fertilizer studies with the exception of Hopmans and Chappell (1994) and Carter et al. (1998), examined naturally self-thinned and mechanically thinned stands derived from natural regeneration. However, in today's forestry practices, forest managers primarily plant genetically improved seedlings from known families with exceptional growth rates. In addition, today's naturally regenerated stands primarily originate from seed-tree silvicultural prescriptions that contain seed from genetically improved trees and plantations are fertilized at younger ages. Our study was designed to enhance our understanding of the growth and yield dynamics of modern plantation forestry as well as alleviate some of the uncertainties associated with forest fertilization.

In our study we measured volume growth of fertilized and nonfertilized young Douglas-fir stands planted with genetically improved seedlings across three different density management regimes. Seven Stand Management Cooperative (SMC) Type I installations were used for this research. Since study establishment, fertilized research plots have received three fertilizer applications at a rate of 224 kg N·ha^{-1} as urea once every 4 years for a cumulative total of 672 kg N·ha^{-1} as urea over 12 years (Maguire et al. 1991). The average breast height (BH) age at the first fertilizer treatment was 6 years. The primary objective of this study was to formulate multiple linear regression equations, which can aid in selecting Douglas-fir stands that will significantly respond to nitrogen fertilization. To achieve this objective, we estimated total volume response due to the cumulative effect of the three fertilization applications (i.e., 12-year response) as well as the 4-year periodic annual increment (PAI) following each fertilizer application (i.e., dependent variables). In addition, a suite of stand, site, and soil variables thought to be important surrogates for estimating fertilization response were measured in the fertilized and nonfertilized plots (i.e., independent variables).

Experimental materials and methods

Study sites

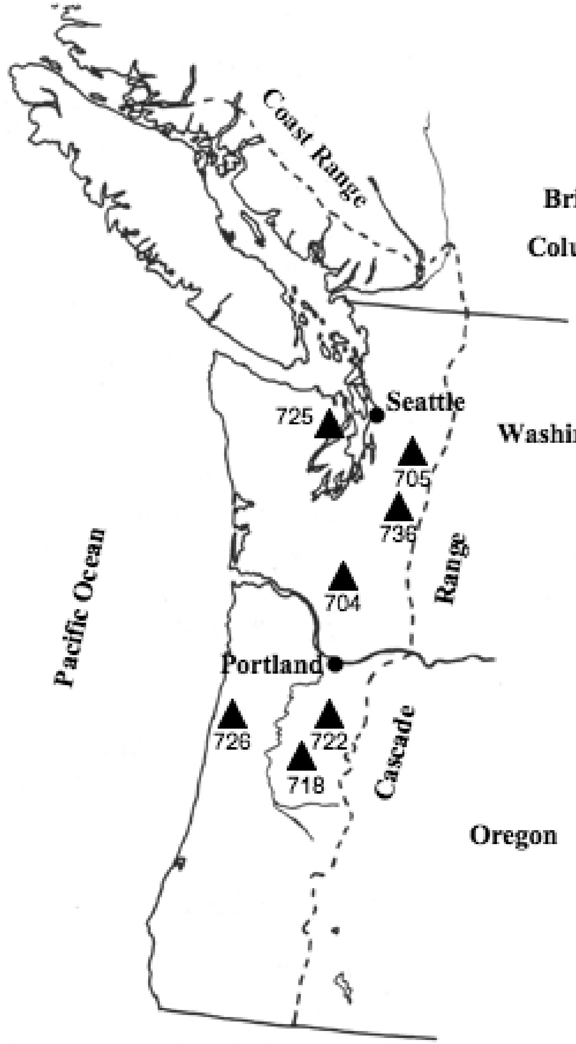
All seven installations are located west of the Cascade crest from central Washington to Oregon (Fig. 1). Stand establishment represents when each study site was planted, whereas study establishment represents the year when treatments began (Table 1). The average Douglas-fir site class for the seven installations was a site class II, which is based on site index. A range of five site classes exists according to King (1966) with a site class I representing an optimum site and a site class V representing a very poor site. The East Twin Creek, Sandy Shore, and Twin Peak installations were the northern-most sites examined and are located on glacial outwash soils. The remaining four installations (Ostrander Rd., Roaring River, Silver Creek, and Toledo) occur on nonglaciated soils with a more developed soil profile than the sites occurring on glacial outwash. The underlying parent material at these sites was either residuum (Ostrander Rd., Roaring River, Silver Creek) or alluvium (Toledo).

Experimental design

Each installation (*N* = 7) represents the blocking factor in a randomized complete block experimental design. At each installation, six 0.2 ha measurement sample plots (47.2 m × 47.2 m) were examined (Fig. 2). Each measurement sample plot (*n* = 42) was surrounded on all four sides by a 9.3 m wide treated buffer strip (Fig. 2). A fertilized and nonfertilized plot for each stand density treatment was measured at each installation (i.e., a 2 × 3 factorial design) (Table 2). The stand density treatments, SD, SD/2, and SD/4, essentially represented a high, medium, and low stocked stand, where the SD/2 treatment contained approximately 50% fewer trees than the SD treatment, and the SD/4 contained approximately 75% fewer trees or only one-quarter of the trees in the SD treatment (Maguire et al. 1991). Each installation contained different initial stand densities prior to thinning and as a result the total number of trees per hectare in each stand density management regime varied slightly across the seven installations.

Each fertilized and nonfertilized plot within the three

Fig. 1. Locations of Stand Management Cooperative (SMC) Type 1 fertilized installations used in this study. All installations occurred west of the Cascade crest, with the three northern-most installations occurring on young recently glaciated soils and the remaining four occurring on older more well-developed soils.



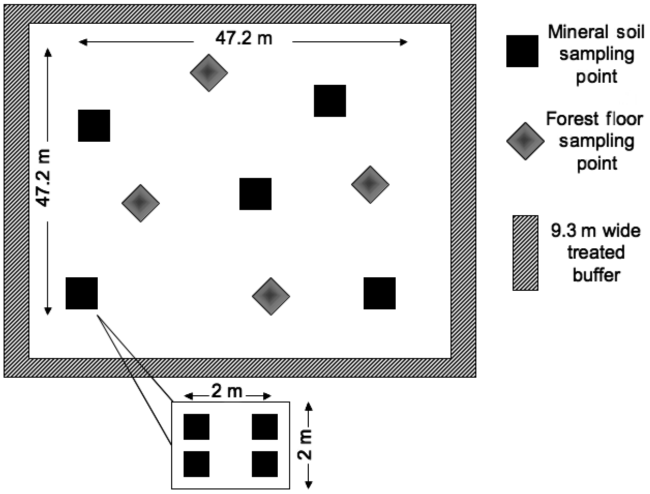
stand density treatments had scheduled thinning regimes when stand density reached a specific value; relative density, which is a function of the basal area and quadratic mean diameter of a stand (Table 3) is a commonly used index for planning time of thinning (Curtis 1982): (*i*) SD had a repeated thinning regime with the first thinning occurring at a relative density of 55 and was thinned to a relative density of 35, the next thinning occurred once the stand exceeded a relative density of 55 the second time, but was only thinned to a relative density of 40, and subsequent thinnings occurred each time the stand exceeded a relative density of 60 and was thinned to a relative density of 40 thereafter, (*ii*) SD/2 had a minimal thinning regime being thinned when the relative density exceeded 55 and was thinned down to a relative density of 35 once, with no further thinnings, and (*iii*) SD/4 received no thinnings.

Each installation was remeasured and fertilized every 4 years. This allowed us to examine 4-year PAI in addition to cumulative volume growth as a dependent variable for the

Table 1. Detailed descriptions of study sites with Stand Management Cooperative installation numbers in parentheses.

	Ostrander Rd. (704)	East Twin Creek (705)	Roaring River (718)	Silver Creek (722)	Sandy Shore (725)	Toledo (726)	Twin Peaks (736)
Latitude	46°12′47.46″	47°10′35.97″	44°39′10.8″	44°52′27″	47°53′49.09″	44°41′29.99″	47°56′53.05″
Longitude	122°50′48.91″	121°43′4.22″	122°42′15.6″	122°33′57.6″	122°46′25.22″	123°56′34.4″	124°27′22.75″
Elevation (m)	600	823	335	671	168	69	183
SI 50 (m)	37	27	39	37	37	41	37
Douglas-fir site class	II	IV	II	II	II	I	II
Average slope (%)	20	30	10	10	0	15	40
Precipitation (mm·year^{-1})	1175	1449	1778	1190	751	1726	1552
Soil texture	Fine-loamy	Loamy-skeletal	Fine	Fine-loamy	Sandy-skeletal	Fine-loamy	Sandy-skeletal
USDA soil suborder	Palehumult	Haplocryod	Palehumult	Dystrudept	Dystroxerept	Dystrudept	Durothod
Stand establishment	1976	1976	1982	1982	1980	1984	1984

Fig. 2. Plot design indicating random sampling locations for the mineral soil and forest floor within each of the measurement sample plots. Cluster sampling was used at each mineral soil sampling point and combined to create composite samples used for soil chemical analysis.



regression equations. Tree volume was calculated using the method outlined by Bruce and deMars (1974).

Soil sampling and chemical analysis

Forest floor and mineral soil samples were collected during the summer of 2004. The mineral soil was sampled at predetermined depths (0–15, 15–30, and 30–50 cm), while the forest floor was sampled using a 30 cm × 30 cm sampling frame (Fig. 2). For the mineral soil, a composite sample was created using a cluster sampling technique (2 m × 2 m area) (Fig. 2). Occasionally an excavation method was used to collect representative mineral soil samples at the designated sampling depths (Canary et al. 2001). This sampling method was only used when soils contained large quantities of coarse fragments (>50% of total soil volume) that inhibited the use of a bucket auger. Composite samples were air dried for a minimum of 1 week and then passed through a 2 mm sieve. Each composite soil sample from the field was spread onto a 25 cm^2 square grid (5 × 5, 1 cm^2 squares), whereby equal proportions of mineral soil from each square were combined to ensure homogeneity for chemical analysis.

Bulk density (D_b) samples for each sampling depth were obtained using a 20 cm tall steel pipe with a 7.65 cm inner diameter. This larger bulk density sampling device was used to capture more cubic volume of soil because of the large amount of variability associated with glaciated soils that contain high quantities of coarse fragments. Bulk density samples were oven dried for 48 h at 105 °C.

Forest floor samples were taken at four random points at each measurement sample plot and were combined to formulate one composite sample per measurement sample plot ($n = 42$). Live herbaceous and woody plants were excluded from the forest floor samples. The principal components of the forest floor sample (e.g., conifer needles, fern litter, moss mat, etc.) and the forest floor thickness were noted. Forest floor samples were oven dried at 70 °C and weighed. Samples were ground through a 2 mm sieve in a No. 3 Wiley Mill (Thomas Scientific, Swedesboro, New Jersey) and prepared for chemical analysis.

Several chemical analyses were performed on the fine-earth soil fraction (<2 mm). The combustion method was used to determine the concentration of N (%N) and C (%C) present in the forest floor and mineral soil (Nelson and Sommers 1982) using a Perkin Elmer model 2400 CHN analyzer (Perkin Elmer, Wellesley, Massachusetts). Total N and C were expressed in kilograms per hectare calculated via the following formula:

$$[1] \qquad D_\mathrm{b}\,(\mathrm{g \cdot cm^{-3}}) \times \text{thickness (cm)} \times [\text{N or C (\%)}] \times 1000$$

Available $\mathrm{NO_3}^-$ and $\mathrm{NH_4}^+$ expressed in milligrams per kilogram were determined using O-I Analytical 500 auto analyzer (O-I Analytical, College Station, Texas). The effective cation exchange capacity ($\mathrm{cmol_c \cdot kg^{-1}}$) was estimated for these soils, because of their inherent high acidity. An unbuffered, 1 $\mathrm{mol \cdot L^{-1}}$ $\mathrm{NH_4Cl}$, solution was used to estimate the effective cation exchange capacity by using a mechanical-syringe extractor. This method has been recommended for estimating forest soil cation exchange capacity (Skinner et al. 2001).

Stand and site variables

The following stand and site variables were measured at each study site: age (years), relative density, quadratic mean diameter (cm), elevation (m), and slope (%). These attributes along with the measured soil properties were included as independent variables during the formulation of the regression equations.

Statistical modeling and analysis

Analysis was conducted in two phases. First, relative cumulative volume response and relative 4-year PAI response following each fertilizer application was calculated for the SD, SD/2, and SD/4 stand density management treatments:

$$[2] \qquad \text{Relative volume response (\%)} = (\mathrm{MV_F} - \mathrm{MV_{NF}})/(\mathrm{MV_{NF}}) \times 100$$

where $\mathrm{MV_F}$ is mean volume of fertilized plots for each stand density management regime (i.e., $n = 7$ for SD, SD/2, and SD/4) and $\mathrm{MV_{NF}}$ is mean volume of nonfertilized plots for each stand density management regime ($n = 7$). Mean volume is the predicted total cumulative volume or 4-year PAI (i.e., net volume growth 4 years after each fertilizer application) from the statistical model (eq. 3). The average volume used to calculate relative response for total cumulative volume and 4-year PAI are volume estimates from the fertilized and nonfertilized plots for each of the three stand density management regimes. These volume estimates calculated by the model standardize the values based on the covariate data eq. 3. Relative volume response was based on measurements taken 4 years following each fertilizer treatment of all individual trees within each plot across all stand density management regimes. Fertilization has occurred at three independent times since study establishment (i.e., once every 4 years). Total cumulative volume and 4-year PAI were chosen as the response variables because they provide both long-term and short-term response trends potentially due to fertilization. Total volume response pro-

Table 2. Initial stand conditions (mean ± SD) for each stand density management regime across all installations measured.

Stand variables	SD	SD/2	SD/4
Breast height age (years)	6±2.18	6±1.98	6±2.04
Trees per hectare	1298±406	596±111	304±51
Volume ($m^3 \cdot ha^{-1}$)	22.41±18.03	10.52±7.54	5.31±3.53
Quadratic mean diamter (QMD, cm)	7.78±1.79	8.04±1.71	8.06±1.78
Basal area (BA, $m^2 \cdot ha^{-1}$)	6.76±4.19	3.22±1.77	1.66±0.84
Relative density ($BA \cdot QMD^{-1/2}$)	2.33±1.22	1.1±0.50	0.56±0.23

Note: SD, unaltered stand density; SD/2, one-half SD; and SD/4, one-quarter SD.

Table 3. Forest floor (FF), mineral soil (MS: 0–15, 15–30, and 30–50 cm), and other site variables used in regression analysis against the unstandardized residuals of the dependent variables (4-year periodic annual increment (PAI) and total cumulative volume) with analytical methods (sample size = 42 for all variables).

Variable	Measurement	Units	Method
1. Age	Stand age	year	Breast height
2. ELEV	Elevation	m	Topography map
3. SI	Site index	m at 30 years	Flewelling et al. 2001
5. RD	Relative density	$BA\ QMD^{-1/2}$	Curtis 1982
6. Slope	Slope	%	Abney level
7. QMD	Quadratic mean diameter	cm	
8. $\%C_{FF}$	Concentration of C	%	Combustion*
9. $\%N_{FF}$	Concentration of N	%	Combustion*
10. C_{FF}	Total C	$kg \cdot ha^{-1}$	
11. N_{FF}	Total N	$kg \cdot ha^{-1}$	
12. C/N_{FF}	C/N ratio		
13. pH_{FF}	pH		Saturated paste
14. $\%C_{MS}$	Concentration of C	%	Combustion*
15. $\%N_{MS}$	Concentration of N	%	Combustion*
16. C_{MS}	Total C	$kg \cdot ha^{-1}$	
17. NW_{MS}	Total N	$kg \cdot ha^{-1}$	
18. C/N_{MS}	C/N ratio		
19. pH_{MS}	pH		1:1 soil–water
20. Avail. $NH_{4(MS)}$	Available NH_4^+	$mg \cdot kg^{-1}$	KCl extraction†
21. Avail. $NO_{3(MS)}$	Available NO_3^-	$mg \cdot kg^{-1}$	KCl extraction†
22. $CEC_{E(MS)}$	Effective CEC	$cmol_c \cdot kg^{-1}$	$1\ mol \cdot L^{-1}\ NH_4Cl$‡

*Nelson and Sommers (1982).

†Keeney and Nelson (1982).

‡Skinner et al. (2001).

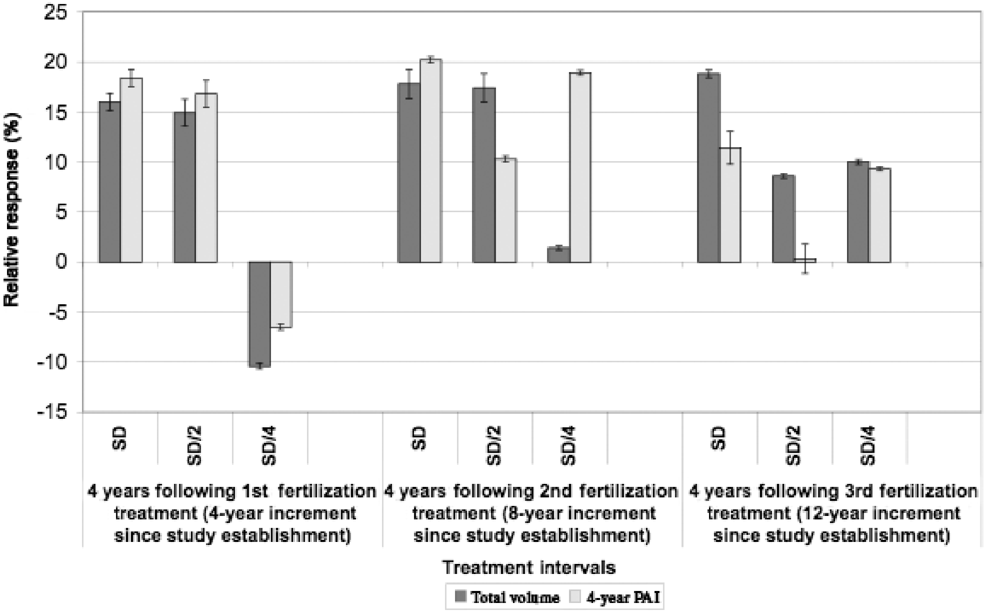
vides the cumulative effects of fertilization on wood production compared with the nonfertilized control treatments since the first fertilization application, whereas 4-year PAI provides the net growth or total wood produced 4 years following each of the three fertilizer applications. This allowed us to examine how effective multiple fertilizations are and whether growth responses are sustained or diminish over time.

The mean volume for the fertilized and nonfertilized plots for each stand density management regime were determined by the output of the following statistical model:

$$[3] \quad y_{ijk} = \mu + \alpha_i + \gamma_j + \alpha\gamma_{ij} + \beta 1 x1_{ijk} + \beta 2 x2_{ijk} + \beta 3 x3_{ijk} + \epsilon_{ijk}$$

where y_{ijk} is Douglas-fir 4-year PAI or total volume for the fertilization level i and thinning level j, μ is the mean Douglas-fir 4-year PAI or volume, α_i is the fixed effect of the ith fertilizer regime, γ_j is the fixed effect of the jth stand density management regime, $\alpha\gamma_{ij}$ is the interaction effect of the ith fertilizer and jth stand density management regime, βs are the slopes of volume against various covariates, $x1_{ijk}$ is the covariate for SI_{30} (Flewelling et al. 2001) for each plot ($n = 42$), $x2_{ijk}$ is the covariate for the initial trees per hectare for each plot before fertilizer treatments began ($n = 42$), and $x3_{ijk}$ is the covariate for breast height age of each plot ($n = 42$). Analysis of covariance (ANCOVA) was used to determine the significance ($\alpha < 0.05$) of fertilization, thinning and the interaction of fertilization and thinning for the plots sampled. This statistical model used conforms to the assumptions typically made for ANCOVA (Neter et al. 1996). These covariates were chosen to make treatment comparisons more precise. This was essential because of differences in stand density, site quality, and breast height age that existed in stands across each installation prior to fertilizer treatments. The Flewelling SI_{30} method was used because it provided specific site indices on a plot-by-plot basis ($n = 42$).

Fig. 3. Mean total volume and 4-year periodic annual increment (PAI) relative response to fertilization (224 kg N·ha^{-1} as urea every 4 years) and thinning with standard errors shown.



In the second phase of analysis the unstandardized residuals of the two dependent variables were regressed against soil, site, and stand variables using stepwise regression. This allowed us to examine which soil, stand, and (or) site variables are the best determinants for selecting sites that would have high probability of responding to fertilization. The unstandardized residuals represent the difference in stand volume from actual field measurements and the stand volume predicted by the model based on the adjustments from the covariates. The data were stratified by the different stand density management regimes ($n = 3$) using the nonfertilized plots only ($n = 21$). During the regression analysis, special attention was given to potential problems associated with multicollinearity. The variance inflation factor (VIF) was used to assess whether multicollinearity was a serious problem for the predictor variables used in the reported regression equations. A VIF less than 10 often indicates that multicollinearity is not an issue and a VIF of 1 indicates there is no multicollinearity (Ott and Longnecker 2001). These assumptions were used for the regression analysis in this study ($\alpha < 0.05$). The VIF is more complete than a Pearson's correlation test because it takes into account all relationships amongst the predictor variables as opposed to examining each predictor variable with the response variable independently (Ott and Longnecker 2001). All statistical analyses were executed using SPSS version 12.0 (SPSS Institute Inc. 2003) statistical software.

Results

Total cumulative volume and 4-year PAI response to multiple fertilizer applications

Four years following the first fertilization treatment (average breast height age 10), the SD and SD/2 fertilized plots had positive growth responses for both total volume and 4-year PAI, while the SD/4 fertilized plots showed no fertilization effect when compared with the nonfertilized plots (Fig. 3). The SD fertilized plots had a 16% response for total volume and an 18% response for 4-year PAI, whereas the SD/2 fertilized plots responded slightly less at 15% and 17% for total volume and 4-year PAI, respectively. The fertilized SD/4 plots responded 10% and 7% less for total volume and 4-year PAI when compared with SD/4 nonfertilized plots.

The ANCOVA for total volume following the first fertilization treatment showed a significant thinning effect, but neither fertilization nor the interaction between fertilization and thinning were statistically significant (Table 4). In regards to 4-year PAI following the first treatment, the ANCOVA showed a significant thinning effect ($p < 0.001$) but no statistically significant fertilization or interaction effects were observed (Table 4). Although fertilization did not cause a significant growth response ($p = 0.059$), growth was substantially higher in the fertilized plots compared with the nonfertilized controls.

During the 4-year period following the second fertilization (8 years since initial fertilization; average breast height age 14), all three stand density treatment regimes had a positive growth response to fertilization for both total volume and 4-year PAI when compared with the nonfertilized plots (Fig. 3). The SD fertilized plots had an 18% response for total volume and a 20% response for 4-year PAI, whereas the SD/2 fertilized plots had a 17% and 10% response for total volume and 4-year PAI, respectively. The SD/4 fertilized plots responded slightly to fertilization for total volume (1%), whereas 4-year PAI had a 19% response to N fertilization during this treatment interval. During this period, all treatment regimes increased in volume by more than 50% since the last treatment interval. The ANCOVA showed that both thinning and fertilization effects were significant for both total cumulative volume ($p < 0.001$; $p = 0.009$) and 4-year PAI ($p < 0.001$; $p = 0.008$), but the interaction between the two remained statistically insignificant (Table 4).

Fertilization response began to diminish during the 4-year

Table 4. ANCOVA *p* values for total volume and 4-year periodic annual increment (PAI) following N fertilizer applications.

	p	
Application period	Total volume	4-year PAI
4 years following first fertilization		
Fertilization	0.213	0.059
Thinning	<0.001	<0.001
Fertilization × thinning	0.363	0.179
4 years following second fertilization		
Fertilization	0.008	0.009
Thinning	<0.001	<0.001
Fertilization × thinning	0.159	0.698
4 years following third fertilization		
Fertilization	0.021	0.461
Thinning	<0.001	0.013
Fertilization × thinning	0.524	0.864

Table 5. Multiple regression equations for the relationships between the unstandardized residuals of total volume ($m^3 \cdot ha^{-1}$) and 4-year periodic annual increment (PAI, $m^3 \cdot ha^{-1} \cdot year^{-1}$) response to 224 kg $N \cdot ha^{-1}$ as urea (dependent variables) and various soil, site, and stand variables (independent variables).

Dependent variable	Equation	*n*	Adjusted R^2	VIF
All DMRs	Total volume = 30.1 – 0.09ELEV	21	0.368	1
	4-year PAI = $-18.4 + 0.01\mathrm{N}_{15\text{–}30\ \mathrm{cm}}$	21	0.174	1
SD	Total volume = $-44.8 + 8.08\mathrm{NO^-}_{3(15\text{–}30\ \mathrm{cm})}$	7	0.611	1
	4-year PAI = $-40.4 + 7.25\mathrm{NH_4^+}_{(15\text{–}30\ \mathrm{cm})} - 19.6\%\mathrm{C}_{15\text{–}30}$	7	0.901	9
SD/2	Total volume = $63.4 - 464.0\%\mathrm{N}_{30\text{–}50\ \mathrm{cm}}$	7	0.833	1
	4-year PAI = $195.083 - 27.0\%\mathrm{C}_{30\text{–}50\ \mathrm{cm}} - 22.6\mathrm{RD}$	7	0.946	4
SD/4	Total volume = Nonsignificant	7	—	—
	4-year PAI = $-36.361 + 0.002\mathrm{C}_{15\text{–}30\ \mathrm{cm}} - 0.015\mathrm{N}_{0\text{–}15\ \mathrm{cm}}$	7	0.930	7

Note: VIF, variance inflation factor; DMR, density management regime; ELEV, elevation; SD, unaltered stand density; SD/2, one-half SD; and SD/4, one-quarter SD; RD, relative density.

period following the third fertilization treatment (12 years since initial fertilization; average breast height age 18), particularly in regards to 4-year PAI. Total volume response was 19% for the SD, 9% for the SD/2, and 10% for the SD/4 plots, whereas the 4-year PAI for all three treatment regimes precipitously dropped following the third treatment (SD = 11%, SD/2 = 0%, and SD/4 = 9%). The ANCOVA for total volume showed significant thinning and fertilization effects ($p < 0.001$; $p = 0.021$) and the interaction between them remained insignificant (Table 4). The ANCOVA for 4-year PAI showed significant thinning effects ($p = 0.013$), while fertilization and the interaction between fertilization and thinning were not significant.

Multiple linear regression prediction equations

Stepwise regression between the unstandardized residuals of the dependent variables (4-year PAI and total volume) from eq. 3 and the independent stand, site, and soil variables explained various degrees of the residual variation (Table 5; Appendix A). When comparing potential relationships for the nonfertilized stand density management regimes ($N = 21$), the best equation included elevation as the sole predictor variable and explained 37% of the residual variation (adjusted $R^2 = 0.368$) (Table 5) for the unstandardized residuals of total volume with a VIF of 1. Relationships between 4-year PAI and stand, site, and soil variables across all stand density management regimes were weak with the best equation explaining only 17% of the residual variation (adjusted $R^2 = 0.174$) (Table 5).

The strongest multiple regression equation for the SD stand density management regime explained 90% of the residual variation (adjusted $R^2 = 0.901$) (Table 5) with 4-year PAI used as the dependent variable. The concentration of NH_4^+ at the 15–30 cm depth explained the majority of the residual variation (60%) and by adding %C at the 15–30 cm depth the amount of variation explained increased by 30%, respectively. The VIF for this equation was 9, which is close to the cutoff where multicollinearity may become a problem. However, if only available NH_4^+ at the 15–30 cm depth were used as a predictor for selecting stands that will likely respond to fertilization the VIF is 1, while still explaining 60% of the residual variation. On the other hand, available NO_3^- at the 15–30 cm depth explained 61% of the total variation (adjusted $R^2 = 0.611$; VIF = 1) (Table 5) for the SD stand density management regime when total cumulative volume was used as the response variable. Inorganic species of N appeared to be the strongest independent predictors for determining the likelihood of a site to respond to fertilization for the SD stand density management regime.

The use of %C at the 30–50 cm depth and relative density (RD) explained the highest amount of residual variation (95%) for the SD/2 stand density management regime when

4-year PAI was used as the dependent variable. This regression equation represented the strongest relationship for any single or combination of soil, stand, or site variables (R^2 = 0.946) (Table 5). The VIF for this equation was moderate with a value of 4. The VIF was 1 when only %C at the 30–50 cm depth was used and explained 64% of the residual variation, while including RD explained an additional 31% of the residual variation without substantially increasing the VIF. The use of %N at the 30–50 cm depth explained 83% of the total variation (R^2 = 0.833) (Table 5) when regressed against total volume and had a VIF of 1.

Only 4-year PAI generated significant regression equations for the SD/4 stand density management regime, whereas no significant regression equations existed for total cumulative volume as a dependent variable. For 4-year PAI, total C at the 15–30 cm depth and total N at the 0–15 cm depth explained 93% of the residual variation (R^2 = 0.93) (Table 5) with a VIF of 7. Total C at the 15–30 cm depth alone explained 81% of the residual variation (adjusted R^2 = 0.811) with a VIF of 1.

Discussion

Relative volume responses across three stand density management regimes

An interaction between stand density treatments and fertilization was not detected when the total cumulative volume and 4-year PAI were examined 12 years following initial fertilization, as well as 4 years following each of the three fertilization applications. However, significant thinning and fertilization effects were observed following each fertilization application for both total volume (except 4 years following the first fertilization application; p = 0.213) (Table 4) and 4-year PAI (except for the 4-year growth period following the third fertilization application; p = 0.461) (Table 4).

Both the SD and SD/2 stand density treatments responded to the first fertilizer application; however, the SD/4 fertilized plots had lower cubic metres of wood per hectare than the nonfertilized SD/4 plots (Fig. 3). The lower growth rates in the fertilized SD/4 plots could be attributed to the expanding understory in these lower density plots. The understory of the SD/4 plots primarily consisted of salal (*Gaultheria shallon* Pursh) with some Oregon grape (*Berberis aquifolium* Pursh). Although not tested statistically, the average percent cover of Oregon grape and salal was 79% in the fertilized SD/4 plots compared with 50% in the nonfertilized plots. The combination of low stand density, stand age, light penetrating the understory and an increase in available water coupled with N fertilization likely increased the growth of these aggressive native understory species, while suppressing the growth of the young Douglas-fir trees in the SD/4 plots. The average breast height age at the time of the first fertilization treatment was 10 years and during this phase of stand development, individual trees are competing for dominance both with surrounding trees as well as the understory (Miller 1995). Although no quantitative data are available, extremely large Douglas-fir branches were also observed in the SD/4 plots; suggesting a potential allometric shift from primarily stem wood production towards more leaf area and larger crowns due to the increased spacing and competition for dominance.

In young conifer stands, salal can be an effective competitor for nutrients (Weetman et al. 1990) and available water (Price et al. 1986). These understory shrubs often proliferate and increase in density following a clearcut and in low density or heavily thinned stands. It is difficult for young seedlings and trees to become established under these circumstances. During the few years following fertilization in these young Douglas-fir stands, the salal cover increased (50%–79%) and was likely a competitor because of increases in nitrogen and root growth. However, as more fertilizer treatments were applied, the competitive effect of the salal and Oregon-grape on Douglas-fir diminished as the stand progressed towards canopy closure (Prescott et al. 1993; Thomas et al. 1999; He and Barclay 2000). In addition to increases in nitrogen, competition for soil water between the understory and young overstory could be an equally valid assumption for explaining the lower growth response observed in the SD/4 stand density treatments following the first fertilization application. Similar studies involving unthinned and thinned stands on similar but slightly drier Douglas-fir sites with over 50% of the stems removed showed: (*i*) similar transpiration rates between the unthinned and thinned Douglas-fir stands and (*ii*) the dense salal understory was consuming over one-half of the available water (Black et al. 1980).

Following the second fertilization application, all stand density management regimes had a significant positive response (p = 0.009 for 4-year PAI) to multiple fertilizer applications (Table 4; Fig. 3). A total of 448 kg N·ha^{-1} as urea had been applied 8 years since study establishment, and all three stand density management regimes at this point had benefited from fertilization. The volume response for the fertilized plots rose from –7% as seen following the first urea application to 19% when compared with the nonfertilized control plots. This further supports the aforementioned speculation that some level of competition occurred between the understory and overstory and that this second dose of urea may have caused a toxicity effect for the salal. It has been reported that salal cover often diminishes with increases in shade (Stanek et al. 1979) and with heavy applications of fertilizer (Prescott et al. 1993; Thomas et al. 1999). More pronounced effects on the reduction of salal cover have been associated with increases in available NH_4^+ and NO_3^- (Prescott et al. 1993) than actual shading because of increases of nitrogen mineralization in the forest floor and mineral soil as a result of multiple fertilizer applications (Fox 2004).

Volume growth following the third fertilization treatment (i.e., 672 kg N·ha^{-1} applied since study establishment) diminished. The actual volume response 4 years following the third fertilization was no longer significant (p = 0.461 for 4-year PAI), but since study establishment, total volume was still significantly higher (p = 0.021) in the fertilized plots than the nonfertilized plots (Table 4). Although we did not do formal cost:benefit analysis, multiple (≥3) fertilizer applications at 224 kg N·ha^{-1} as urea may not be cost-effective, since the majority of the volume response occurred during the 8-year period following the first two fertilizer applications. Many Douglas-fir studies have shown significant growth responses to multiple fertilization applications (Chappell et al. 1991; Weetman et al. 1997), but few have examined how this response diminishes with each additional fertilizer application. This is why we examined and compared fertilization response for total cumulative volume between the fertilized and nonfertilized plots after three fertilizer applications as well as the actual volume gained following each of the three fertilizer applications individually (i.e., 4-year PAI). We do not discount that multiple fertilizations are not cost-effective all the time, but merely suggest that the cost-effectiveness of fertilization is a function of both frequency and rate of application. Studies that have applied frequent lower rates of fertilizer (every 1–2 years) have shown greater tree response than single large doses of fertilizers (Van Miegroet et al. 1994) as well as higher N-mineralization rates, which ultimately increase N availability in these stands (Fox 2004).

Many other nutrients such as P, K, S, Mg, and Ca were not measured. These other macronutrients might have helped explain the variability in volume response that was observed across sites. A total of 672 kg N·ha^{-1} as urea was applied on the fertilized plots. This relatively high dosage over a 12-year period could induce other nutrient deficiencies as the system becomes saturated with N. In particular, these high N additions over a relatively short period could cause increased nitrification and leaching (Aber et al. 1998), resulting in loss of base cations such as Ca and Mg (Johnson and Cole 1980). These cause and effect relationships may reduce the responsiveness of the stand to N fertilization treatments because of developing nutrient deficiencies. If this becomes an issue, the formulation of proper fertilizer blends may alleviate this potential side effect of excessive N. Since pretreatment soil samples were not taken, it is difficult to determine the absolute effect that N fertilization had on other soil chemical properties.

Regression equations

Regression equations were created by either pooling all stand density management regimes into one class or by stratifying them by each stand density management regime (Table 5). Weak relationships were found when pooling all the stand density management regimes into one class. However, stratifying total volume and 4-year PAI by stand density management regime improved the variability accounted for by our statistical model. This was consistent with the results from Edmonds and Hsiang (1987) who reported an improvement in predicting response to fertilization when data were stratified by thinning regimes, geographic location, and site class. Stratifying by density management regime allowed us to examine the potential effects associated with different levels of competition, sunlight, and nutrient use due to the variations in growing space.

Two key criteria were examined prior to selecting the presented regression equations: (*i*) the VIF values, which helped avoid potential problems associated with multicollinearity and (*ii*) the number of predictor variables within each equation (Table 5). Regression equations that contain too many independent variables become difficult to implement in a field setting. For example, if the adjusted R^2 did not increase substantially with the addition of other variables, then preference was given to equations with one or two variables. In many cases, as the number of variables exceeded two, multicollinearity became a major concern because VIF values were often >10. The majority of the predictor variables used within the equations (Table 5) were some variant of C and N. Specifically, either total C and N, or NH_4^+ and NO_3^- or %C and %N. Studies have shown that total C and N, such as the C/N ratio and total N of the forest floor are highly correlated to fertilization response for Douglas-fir (Peterson et al. 1984; Edmonds and Hsiang 1987). In this study, no significant relationships were observed between fertilization response and total N and the C/N ratios of the forest floor (Hopmans and Chappell 1994); however, mineral soil %C, %N, NH_4^+, NO_3^-, total C, and total N significantly increased the amount of residual variation explained by our models. Potential explanations in regards to differences between the results from Hopmans and Chappell (1994) and this study and the Peterson et al. (1984) and Edmonds and Hsiang (1987) studies could be associated to the younger age at which fertilization began, lower leaf litter inputs, thinner forest floor, spacing, and (or) seedling genetics.

Earlier studies were primarily conducted in older naturally regenerated self-thinned or mechanically thinned Douglas-fir stands. Our study differs from previous studies because we sampled at four distinct soil profile depths (i.e., forest floor and three mineral soil samples) and had three stand density management regimes. Other studies that have sampled soil only sampled the forest floor and mineral soil at the 0–15 cm depth (Peterson et al. 1984; Edmonds and Hsiang 1987) or the 0–15 cm mineral soil depth only (Miller et al. 1989). These mineral soil depths would represent the majority of the A horizon. However, we sampled to a depth of 50 cm to capture the majority of the rooting zone responsible for nutrient uptake.

Concentrations of C, N, NH_4^+, and NO_3^- explained the majority of fertilization responses in the SD and SD/2 regression equations and total C and N at various depths explained fertilization response for the SD/4 regression equations. In particular, available NH_4^+ and NO_3^- often limits stand productivity because forests in the Pacific Northwest are largely N limited (Gessel et al. 1973). These results show the importance of total and inorganic species of N as well as total C as a proxy for estimating Douglas-fir growth response to urea fertilization, whereas stand and site variables such as relative density and elevation playing a minor role. Consequently, these equations can be used to determine which stands would most likely respond to fertilization. The findings in this study provide insight into potential explanations regulating fertilization response in young Douglas-fir stands with an emphasis on C and N.

Conclusions

Interpretation and comparison of the results from this study with previous research requires a clear understanding of the differences. This study is (*i*) based on plantations with a range of thinning treatments rather than on natural stands, (*ii*) initiated fertilization treatment at a younger age, average breast height age was 6 years, and (*iii*) all but two of the installations sampled in this study had a Douglas-fir site class II rating (King 1966).

The findings from this study show that growth response from N fertilization diminishes over time. Our results indicated a positive cumulative growth response of Douglas-fir to urea fertilization since treatments began 12 years ago; however, the effectiveness of repeated application of urea at a rate of 224 kg N·ha^{-1} as urea every 4 years diminished during the last treatment application (i.e., 4-year growth period following final fertilizer application).

The regression analysis showed that the most influential variables were concentrations of C, N, NH_4^+, and NO_3^-, while stand and site variables contributed very little to the total variation explained. Miller et al. (1989) concluded that stand attributes were the best predictor variables when predicting Douglas-fir growth response to urea in western Oregon and that soil variables were not a cost-effective method for increasing the predictability of fertilizer response. Several significant regression equations included soil chemical data that contributed considerably towards the overall variation explained by the regression equations, suggesting that the cost of soil sampling and analysis is a cost-effective method for estimating stand responsiveness to N fertilization treatments. However, we recognize potential limitations due to a relatively small sample size but long-term fertilization trials in Douglas-fir plantations are expensive and are not as omnipresent as fertilization trials of the 1960s and 1970s that utilized natural plantations. The results from this study show the need for more extensive and highly replicated fertilization trials to corroborate these findings. This would allow forest managers to select stands that have a high probability of generating large financial returns because of growth responses associated with forest fertilization.

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References

Aber, J., McDowell, W., Nadelhoffer, K., Magill, A., Bernston, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L., and Fernandez, I. 1998. Nitrogen saturation in temperate forest ecosystems: hypotheses revisited. Bioscience, **48**: 921–934. doi:10.2307/1313296.

Black, T.A., Tan, C.S., and Nnyamah, J.U. 1980. Transpiration rate of Douglas-fir trees in thinned and unthinned stands. Can. J. Soil Sci. **60**: 625–631.

Blake, J.J. 1985. Characterization of soil nitrogen and sulfur availability in relation to volume response of Douglas-fir. [*Pseudotsuga menziesii* (Mirb.) Franco] in western Oregon and Washington. Ph.D. dissertation, University of Washington, Seattle.

Briggs, D., and Trobaugh, J. 2001. Management practices on Pacific Northwest west-side industrial forest lands, 1991–2000: with projections to 2005. Stand Management Cooperative. SMC Working Paper No. 2. Coll. For. Res. University of Washington, Seattle.

Bruce, D., and DeMars, D.J. 1974. Volume equations for second-growth Douglas-fir (*Pseudotsuga menziesii*). USDA For. Serv. Res. Note PNW-239.

Canary, J.W., Harrison, R.B., Compton, J.E., and Chappell, H.N. 2001. Additional carbon sequestration following repeated urea fertilization of second-growth Douglas-fir stands in western Washington. For. Ecol. Manage. **138**: 225–232. doi:10.1016/S0378-1127(00)00398-4.

Carter, R.E., McWilliams, E.R.G., and Klika, K. 1998. Predicting response of coastal Douglas-fir to fertilizer treatments. For. Ecol. Manage. **107**: 275–289. doi:10.1016/S0378-1127(97)00346-0.

Chappell, H.N., Cole, D.W., Gessel, S.P., and Walker, R.B. 1991. Forest fertilization research and practice in the Pacific Northwest. Fert. Res. **27**: 129–140. doi:10.1007/BF01048615.

Curtis, R.O. 1982. A simple index of stand density for Douglas-fir. For. Sci. **28**: 92–94.

Edmonds, R.L., and Hsiang, T. 1987. Forest floor and soil influence on response of Douglas-fir to urea. Soil Sci. Soc. Am. J. **51**: 1332–1337.

Flewelling, J., Collier, R., Gonyea, B., Marshall, D., and Turnblom, E. 2001. Height–age curves for planted Douglas-fir, with adjustments for density. Stand Management Cooperative. SMC Working Paper No. 1. Coll. For. Res., University of Washington, Seattle.

Fox, T.R. 2004. Nitrogen mineralization following fertilization of Douglas-fir forests with urea in western Washington. Soil Sci. Soc. Am. J. **68**: 1720–1728.

Gessel, S.P., Cole, D.W., and Steinbrenner, E.C. 1973. Nitrogen balance in forest ecosystems of the Pacific Northwest. Soil Biol. Biochem. **5**: 19–34. doi:10.1016/0038-0717(73)90090-4.

He, F., and Barclay, H.J. 2000. Long-term response of understory plant species to thinning and fertilization in a Douglas-fir plantation on southern Vancouver Island, British Columbia. Can. J. For. Res. **30**: 566–572. doi:10.1139/cjfr-30-4-566.

Hopmans, P., and Chappell, H.N. 1994. Growth response of young, thinned Douglas-fir stands to nitrogen fertilizer in relation to soil properties and tree nutrition. Can. J. For. Res. **24**: 1684–1688. doi:10.1139/x94-217.

Johnson, D.W., and Cole, D.W. 1980. Anion mobility in soils: relevance to nutrient transport from forest ecosystems. Environ. Int. **3**: 79–90. doi:10.1016/0160-4120(80)90040-9.

Keeney, D., and Nelson, D.W. 1982. Inorganic-nitrogen forms. *In* Methods of soil analysis. Part 2. *Edited by* A.L. Page et al. 2nd ed. Agronomy, **9**: 643–698.

King, J. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forestry Paper No. 8, July 1966. Weyerhaeuser Company, Forestry Research Center, Centralia, Wash.

Maguire, D.A., Bennett, W.S., Kershaw, J.A., Jr., Gonyea, R., and Chappell, H.N. 1991. Stand Management Cooperative silviculture project field installations: establishment report. Contribution No. 72. Inst. For. Res. Coll. For. Res. University of Washington, Seattle.

Miller, H.G. 1995. The influece of stand development on nutrient demand, growth and allocation. Plant Soil, **168–169**: 225–232. doi:10.1007/BF00029332.

Miller, R.E., Barker, P.R., Peterson, C., and Webster, S.R. 1986. Using nitrogen fertilizers in management of coast Douglas-fir. I. Regional trends of response. *In* Douglas-fir: stand management for the future. *Edited by* C.D. Oliver et al. Proceedings of a Symposium. Seattle, Wash. 18–20 June 1985. Contrib. No. 55. College of Forest Resources, University of Washington, Seattle, Wash. pp. 290-303.

Miller, R.E., McNabb, D.H., and Hazard, J. 1989. Predicting Douglas-fir growth and response to nitrogen fertilization in western Oregon. Soil Sci. Soc. Am. J. **53**: 1552–1560.

Mitchell, A.K., Barclay, H.J., Brix, H., Pollard, D.F.W., Benton, R., and deJong, R. 1996. Biomass and nutrient element dynamics in Douglas-fir: effects of thinning and nitrogen fertilization over 18 years. Can. J. For. Res. **26**: 376–388. doi:10.1139/x26-042.

Nelson, D.W., and Sommers, L.E. 1982. Total carbon, organic carbon and organic matter. *In* Methods of soil analysis. Part 2. *Edited by* A.L. Page et al. 2nd ed. Agronomy, **9**: 539–579.

Neter, J., Kutner, M.H., Nachtsheim, C.J., and Wasserman, W. 1996. Applied linear regression models. 3rd ed. Irwin, Homewood, Ill.

Omule, S.A.Y. 1990. Net basal area response 9 years after fertilizing thinned and unthinned Douglas-fir. FRDA Report 029. Research Branch, B.C. Ministry of Forests, Victoria.

Opalach, D., Heath, L.S., and Chappell, H.N. 1987. Growth response to single and multiple nitrogen fertilizer applications in thinned Douglas-fir stands. Unpublished, RFNRP Report No 8. Coll. For. Res. University of Washington, Seattle.

Ott, R.L., and Longnecker, M. 2001. An introduction to statistical methods and data analysis. 5th ed. Thomson Learning, Inc., Duxbury Press, Pacific Grove, Calif.

Peterson, C.E., and Heath, L.S. 1986. Volume growth and volume growth response after fertilization of unthinned Douglas-fir stands. RFNRP Report No 6. Coll. Forest Resources, University of Washington, Seattle.

Peterson, C.E., Ryan, P.J., and Gessel, S.P. 1984. Response of Northwest Douglas-fir stands to urea: correlations with forest soil properties. Soil Sci. Soc. Am. J. **48**: 162–169.

Powers, R.F. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Sci. Soc. Am. J. **44**: 1314–1320.

Prescott, C.E., Coward, L.P., Weetman, G.F., and Gessel, S.P. 1993. Effects of repeated fertilization on the ericaceous shrub, salal (*Gaultheria shallon*), in two coastal Douglas-fir forests. For. Ecol. Manage. **61**: 45–60. doi:10.1016/0378-1127(93)90189-T.

Price, D.T., Black, T.A., and Kelliher, F.M. 1986. Effects of salal understory removal on photosynthetic rate and stomatal conductance of young Douglas-fir trees. Can. J. For. Res. **16**: 90–97.

Radwan, M.A., and Shumway, J.S. 1984. Site index and selected soil properties in relation to response of Douglas-fir and western hemlock to nitrogen fertilizer. *In* Forest soils and treatment impacts. *Edited by* E.L. Stone. Proceedings of the 6th North American Forest Soils Conference, Knoxville, Tenn. 19–23 June 1983. University of Tennessee Press, Knoxville. pp. 89–104.

Shumway, J.S., and Atkinson, W.A. 1978. Predicting nitrogen fertilizer response in unthinned stands of Douglas-fir. Commun. Soil. Sci. Plant Anal. **9**: 529–539.

Skinner, M.F., Zabowski, D., Harrison, R., Lowe, A., and Xue, D. 2001. Measuring the cation exchange capacity of forest soils. Commun. Soil. Sci. Plant Anal. **32**: 1751–1764. doi:10.1081/CSS-120000247.

SPSS Institute Inc.. 2003. SPSS for Windows. Rel. 12.0.0. SPSS Institute Inc., Chicago.

Stanek, W., Beddows, D., and State, D. 1979. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake on Vancouver Island: some observations on salal and bracken fern undergrowth. Can. For. Serv. Pac. For. Res. Cent. Inf. Rep. BC-R-1.

Stegemoeller, K.A., and Chappell, H.N. 1991. Effects of fertilization and thinning on 8-year growth- responses of second-growth Douglas-fir stands. Can. J. For. Res. **21**: 516–521.

Strader, R.H., and Binkley, D. 1989. Mineralization and immobilization of soil nitrogen in two Douglas-fir stands 15 and 22 years after nitrogen fertilization. Can. J. For. Res. **19**: 798–801. doi:10.1139/x89-121.

Thomas, S.C., Halpern, C.B., Falk, D.A., Liguori, D.A., and Austin, K.A. 1999. Plant diversity in managed forests: understory responses to thinning and fertilization. Ecol. Appl. **9**: 864–879. doi:10.1890/1051-0761(1999)009[0864:PDIMFU]2.0.CO;2.

Turner, J., Lambert, M.J., and Gessel, S.P. 1977. Use of foliage sulphate concentrations to predict response to urea application by Douglas-fir. Can. J. For. Res. **7**: 476–480. doi:10.1139/x77-061.

Turner, J., Lambert, M.J., and Gessel, S.P. 1979. Sulfur requirements of nitrogen fertilized Douglas-fir. For. Sci. **25**: 461–467.

Turner, J., Lambert, M.J., and Gessel, S.P. 1988. Nitrogen requirements in young Douglas-fir of the Pacific Northwest. Fert. Res. **15**: 173–179. doi:10.1007/BF01050679.

Van Miegroet, H., Norby, R.J., and Tschaplinski, T.J. 1994. Nitrogen fertilization strategies in a short-rotation sycamore plantation. For. Ecol. Manage. **64**: 13–24. doi:10.1016/0378-1127(94)90123-6.

Weetman, G.F., Fournier, R.M., Schnorbus-Panozzo, E., and Barker, J. 1990. Post-burn nitrogen and phophorus availability in coastal British Columbia cedar/hemlock forests and the use of fertilization and salal eradication to restore productivity. *In* Sustained productivity of forest lands. *Edited by* S.P. Gessel. Proceedings of the Seventh North American Forest Soils Conference, University of British Columbia, Vancouver, B.C. Friesen Press, Vancouver, B.C. pp. 451–499.

Weetman, G.F., Prescott, C.E., Kohlberger, F.L., and Fournier, R.M. 1997. Ten-year growth response of coastal Douglas-fir on Vancouver island to N and S fertilization in an optimum nutrition trial. Can. J. For. Res. **27**: 1478–1482. doi:10.1139/cjfr-27-9-1478.

Appendix A

Appendix A appears on the following page.

Table A1. Summarized soil chemical data (mean ± SD) for fertilized and nonfertilized plots by stand density management regime.

Variable*	SD	SD/2	SD/4
Age	19±4.0	19±4.0	19±4.0
ELEV	347±269	347±269	347±269
PPT	1374±362	1374±362	1374±362
Slope	19±12.0	19±12.0	19±12.0
SI_{30}	25.75±2.45	26.2±3	26±2.5
RD	6.45±0.75	5.85±0.79	3.75±0.77
QMD	22.9±1.9	26.6±1.6	31±2.6
$\%C_{FF}$	35.7±4.95	36.8±3.30	36.6±5.40
$\%C_{0\text{–}15\ \mathrm{cm}}$	5.71±1.80	5.66±1.90	5.89±1.90
$\%C_{15\text{–}30\ \mathrm{cm}}$	3.63±1.75	3.53±1.45	3.63±1.25
$\%C_{30\text{–}50\ \mathrm{cm}}$	2.85±1.35	2.34±0.75	2.75±0.90
$\%N_{FF}$	1.13±0.20	1.24±0.23	1.3±0.28
$\%N_{0\text{–}15\ \mathrm{cm}}$	0.275±0.13	0.25±0.1	0.28±0.11
$\%N_{15\text{–}30\ \mathrm{cm}}$	0.185±0.12	0.17±0.07	0.19±0.08
$\%N_{30\text{–}50\ \mathrm{cm}}$	0.155±0.10	0.13±0.05	0.15±0.06
C_{FF}	4801±1774	4709±1879	4500±2090
$C_{0\text{–}15\ \mathrm{cm}}$	52790±18780	51685±16535	53385±16395
$C_{15\text{–}30\ \mathrm{cm}}$	41690±20020	39755±16060	41570±13885
$C_{30\text{–}50\ \mathrm{cm}}$	45055±17795	37585±12125	43310±17125
N_{FF}	158±76.0	166±92	165±83.0
$N_{0\text{–}15\ \mathrm{cm}}$	2515±1108	2305±892	2460±894
$N_{15\text{–}30\ \mathrm{cm}}$	2100±1190	1885±737	2095±738
$N_{30\text{–}50\ \mathrm{cm}}$	2445±1203	1920±704	2235±712
C/N_{FF}	32.5±6.1	30.5±5.2	29±4.0
$C/N_{0\text{–}15\ \mathrm{cm}}$	21.5±3.2	23±3.3	22±3.1
$C/N_{15\text{–}30\ \mathrm{cm}}$	20.5±4.3	21.5±5.6	20±3.0
$C/N_{30\text{–}50\ \mathrm{cm}}$	19±3.9	20±4.9	19±4.6
pH_{FF}	4.85±0.3	4.85±0.3	4.9±0.3
$pH_{0\text{–}15\ \mathrm{cm}}$	4.8±0.3	4.7±0.4	4.85±0.3
$pH_{15\text{–}30\ \mathrm{cm}}$	4.95±0.2	4.9±0.3	4.95±0.3
$pH_{30\text{–}50\ \mathrm{cm}}$	5±0.1	4.9±0.3	5±0.3
Avail. $NH_4^+{}_{(0\text{–}15\ \mathrm{cm})}$	22.25±6.4	17.1±6.5	21.3±7.5
Avail. $NH_4^+{}_{(15\text{–}30\ \mathrm{cm})}$	15.65±6.5	14±5.9	16.7±5.3
Avail. $NH_4^+{}_{(30\text{–}50\ \mathrm{cm})}$	13.2±6.5	12.8±5.7	13.5±4.8
Avail. $NO_3^-{}_{(0\text{–}15\ \mathrm{cm})}$	22.35±27.2	10.2±11.0	22.7±31.0
Avail. $NO_3^-{}_{(15\text{–}30\ \mathrm{cm})}$	14.05±17.5	6.05±6.8	10.7±12.8
Avail. $NO_3^-{}_{(30\text{–}50\ \mathrm{cm})}$	11.1±12.8	6.1±6.1	10.4±12.8
$CEC_{E(0\text{–}15\ \mathrm{cm})}$	18.1±9.3	17.8±7.4	17.6±7.4
$CEC_{E(15\text{–}30\ \mathrm{cm})}$	15.5±9.1	18.1±8.5	16±7.6
$CEC_{E(30\text{–}50\ \mathrm{cm})}$	18.1±10.0	18.4±9.4	16.4±8.1

*PPT, precipitation ($\mathrm{mm{\cdot}year^{-1}}$). See Table 3 for description of units and methodology for each variable.