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Response of Northwest Douglas-fir Stands to Urea: Correlations with Forest Soil Properties

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ABSTRACT

Replicated forest floor and surface soil (0–15 cm) samples were obtained from control plots at 160 field installations to western Washington and Oregon. Six year growth responses of thinned and unthinned Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in stallations treated with 0, 224, and 448 kg of urea-N ha^{-1} were correlated with 18 forest floor and surface soil properties of the control plots. Correlations for response with respective forest floor and soil data were produced for levels of fertilizer application and both basal area and volume response. Observed and estimated expressions of absolute and relative response were used in analyses. Forest floor nitrogen properties were the most highly correlated with various estimates of response in both thinned and unthinned stands; these correlations were generally independent of methods used to estimate response. For unthinned stands, C/N ratios of both forest floor and surface soil were well correlated with growth response to fertilizer, whereas for thinned stands, N content (kilograms per hectare) of the forest floor was consistently correlated with response.

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NITROGENOUS FERTILIZER has been applied to Douglas-fir stands on an operational basis for about 10 yr in the Pacific Northwest (Bengston, 1979) and over 1 million ha have been treated. Considerable land area has had at least one repeat application of nitrogen. In most instances nitrogen has been applied as urea at a rate of 224 kg ha^{-1} as elemental N. This aspect of intensive management emphasizes the longrun expectation of increased growth rate from nitrogen fertilization by both public and private forest landowners. A major source of information for Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] growth response in the Northwest has been the Regional Forest Nutrition Research Project (RFNRP). The project was initiated in 1969 as a cooperative effort to determine average regional growth response of Douglas-fir and western hemlock [*Tsuga heterophylla* (Raf) Sarg.] stands to nitrogen fertilizer. Response has been defined for this study as the increase (or decrease) in PAI (periodic annual increment) due to fertilization. Only the Douglas-fir results are reported in this paper.

Regional average 6-yr response to urea N is statistically significant in both unthinned and thinned stands and for both rates of urea-N application (224 and 448 kg ha^{-1}). Information on response magnitude, statistical significance, and duration of response were presented by the RFNRP staff (1980, 1982). The net and gross growth rates of fertilized and unfertilized plots, application rates, and differential mortality were presented for thinned and unthinned stands by Peterson and Gessel (1983). Stand variables such as site index and stocking have been used in regression (Turnbull and Peterson, 1976) to explain some of the regional response variation. However, the relationship of soil and site properties to regional growth response has not received a comprehensive examination.

Soil and physiographic variables have been introduced to growth response models in hopes of making the models more site specific by explaining regional growth variation (Kushla and Fisher, 1980). Both correlation and regression analyses have been used extensively in growth response analysis (Wells, 1970; Lea and Ballard, 1982), and in some instances models have been developed and used to classify areas as being responsive and nonresponsive (Comerford and Fisher, 1982).

The magnitude and longevity of response may be greatly influenced by the measure of growth used to calculate response (Comerford et al., 1980). We recognize this as an additional problem in considering soil properties whose correlation with response varies according to the type of response estimate used. Therefore, the approach adopted for this study is one of classifying types of response estimates, subjecting each type to analysis, and examining the results for consistency (recurring patterns independent of methods used to estimate response).

Our objective in this paper is to identify relevant soil properties and correlate them directly to various expressions of growth response as wood production. We present this analysis for both applications of fertilizer, with and without thinning. Volume PAI is of primary interest for economical justification of operational fertilization. However, basal area PAI was also analyzed for response and correlation with soil properties since it was sampled and measured with less error than the volume growth rate.

METHODS

Experimental Design

Field installations, considered as blocks in a random complete blocks design, were established in western Washington and western Oregon (Fig. 1). Each installation contains two plots per treatment: no fertilizer (controls), 224 kg ha^{-1} of urea N (224N), and 448 kg ha^{-1} urea N (448N). Each plot had a minimum area of 0.04 ha. Young second growth stands of unmanaged Douglas-fir were of primary interest. Wellstocked (85-120% "normal," McArdle and Meyer, 1930) unthinned stands were purposively selected and arrayed into breast height age classes of 10 to 50 yr and site classes 1 through 4 (King, 196b). A random selection from these stands was then made for establishment of 85 unthinned installations fertilized in 1969 to 1970 and 35 installations that were thinned (six plots) to 60% of the original basal area and fertilized in 1971 to 1972. The thinned installations had two additional

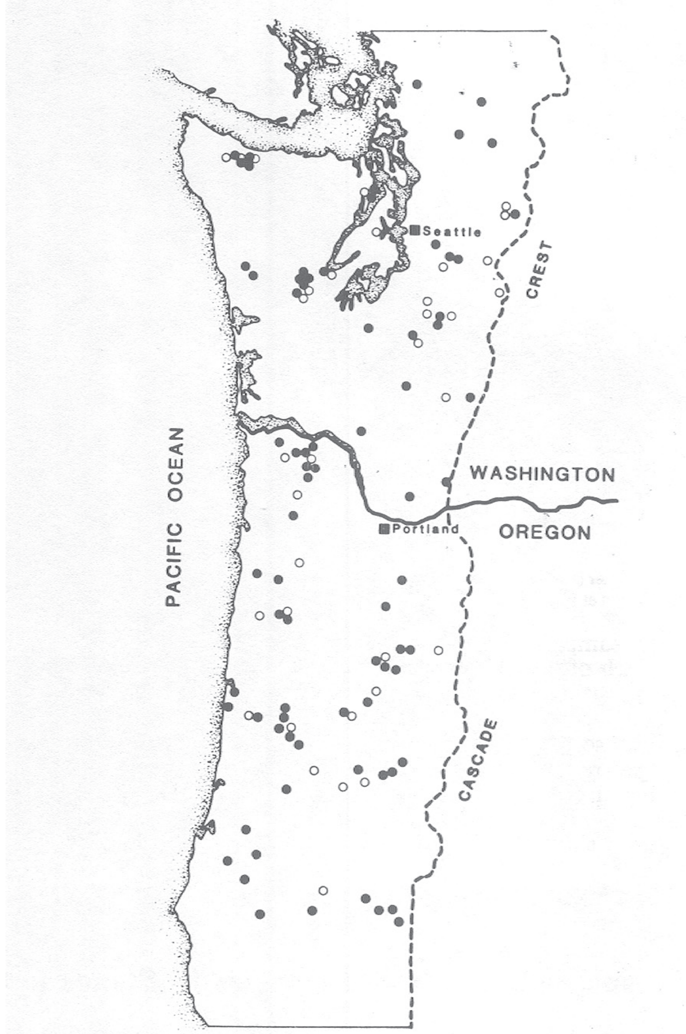

Fig. 1—RFNRP fertilizer trials; regional coverage of unthinned (●) and thinned (○) installations.

0.01-ha plots unthinned and unfertilized that were representative of prethinned stand conditions.

Field Measurements

Trees

Initial measurements of diameter were taken for all trees in the plot. The only heights measured were samples needed to estimate site index (King, 1966) and to estimate volume, using tarifs (Turnbull et al., 1972). These heights and diameters were remeasured every 2 yr.

Soils

The objective in soil sampling was to characterize the forest soils before thinning, fertilization, or both. At the time of installation establishment, two composited soil samples were derived from 20 (7.6 cm diam) cores of surface soil (0-15 cm) randomly sampled on each of the two unthinned unfertilized plots. These samples were air-dried and fineearth fraction (<2 mm) retained for analysis. Two forest floor samples of a known area (0.09 m^2) were also sampled in each of these plots, dried at 70°C for 48 h, and comminuted using a Waring blender. The <2-mm fraction was then retained for analysis. The method of analysis, coding, and descriptive statistics for

Table 1—Methods of analysis and descriptive statistics for the forest floor and soil properties of the combined unthinned and thinned Douglas-fir installations.

Variable	Measurement	Procedure (Reference)	Mean ± SD	Max.	Min.	Sample size
		A. Forest floor (FF)				
1. FF-TW	Total weight, kg ha^{-1}		21 998 ± 10 003	88 917	6 649	120
2. FF-%N	Total N, %	Kjeldahl method†	0.93 ± 0.16	1.48	0.51	120
3. FF-%C	Total C, %	LECO combustion method‡	36.9 ± 5.16	48.9	22.2	118
4. FF-N	Nitrogen weight, kg ha^{-1}		202 ± 79	613	49	120
5. FF-C	Carbon weight, kg ha^{-1}		8 033 ± 2 913	19 766	1 955	118
6. FF-C/N	C/N ratio		40.4 ± 5.8	57.1	27.1	118
		B. Surface soil, 0–15 cm				
7. SS-%N	Total N, %	Kjeldahl method†	0.22 ± 0.12	0.88	0.07	117
8. SS-%C	Total C, %	LECO combustion method‡	5.70 ± 2.57	18.25	2.23	117
9. SS-C/N	C/N ratio		27.3 ± 5.9	44.5	16.3	117
10. SS-TOTP	Total P, ppm	$HClO_4$ digestion§	1 176.0 ± 509.0	2 346.0	211.8	120
11. SS-AVP	Available P, ppm	Bray <2 extraction§	67.3 ± 50.8	322.0	4.0	120
12. SS-AVS	Available S, ppm	K_2HPO_4 extraction¶	6.9 ± 4.1	20.5	2.0	120
13. SS-PH	pH	1:1 soil-water suspensions	5.18 ± 0.39	6.55	4.18	117
14. SS-EXCA	Exchangeable Ca, cmol(p+)kg^{-1}	1*N* NH_4OAc extraction§	4.26 ± 2.74	12.99	0.38	120
15. SS-EXMG	Exchangeable Mg, cmol(p+)kg^{-1}	1*M* NH_4OAc extraction§	1.16 ± 0.80	5.18	0.15	120
16. SS-EXK	Exchangeable K, cmol(p+)kg^{-1}	1*N* NH_4OAc extraction§	0.57 ± 0.30	1.71	0.08	119
17. SS-CEC	CEC, cmol(p+)kg^{-1}	1*N* NH_4OAc extraction§	32.04 ± 9.80	69.50	7.70	119
18. SS-BSAT	Base saturation, %		20.0 ± 12.2	55.7	2.4	119

† Bremner (1965). § Jackson (1958).
‡ Allison et al. (1965). ¶ Ensminger (1954).

the soil and forest floor properties are listed in Table 1. In addition to this surface sampling, a soil pit was excavated in the buffer zones of the control plots and described using the methods of the Soil Survey staff (1951).

Statistical Analysis

Since this current work was intended to identify soil and site variables that were related to response (not necessarily causal relationships), we adopted a parsimonious approach and limited our analysis to simple correlations of response with soil properties and site index. Forest floor and surface soil properties were averaged for each installation; a total of 84 unthinned and 35 thinned installations were used. Growth increment, age, site index, and basal area were averaged by treatment within an installation; no transformations were used on any of the data.

Observed response was taken to be the difference between average treatment PAI and average control PAI at each installation. Estimated response was computed as the difference between average treatment PAI and the estimated control PAI for the installation, where the control PAI was estimated from a regional regression fitted to control PAI from all installations as a function of installation age, site index, and basal area.

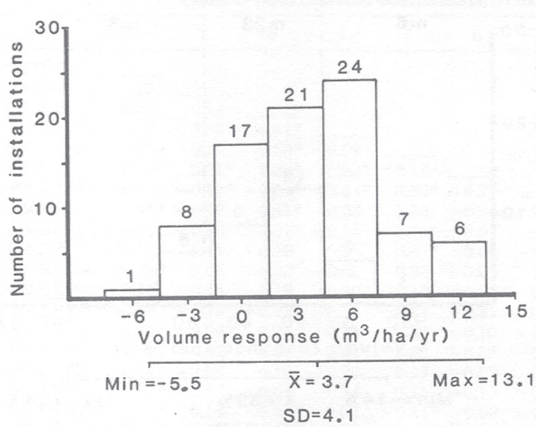

Fig. 2—Unthinned Douglas-fir observed 6-yr absolute volume increment response to 448 kg of N ha^{-1} treatment.

Both absolute differences (m^2 ha^{-1} yr^{-1} and m^3 ha^{-1} yr^{-1}) and relative increases over control growth rate were analysed for both rates of nitrogen application. The range of response after 6 yr to 448 kg ha^{-1} in unthinned plots is given in Fig. 2 and 3. Response in thinned plots is presented in Fig. 4 and 5.

Observed and estimated expressions of absolute and relative response at each installations were categorized as low, average, or high (according to relative response) and symbolized as LO, AVE, and HI in Fig. 3 and 5. We arbitrarily placed installations responding <10% in the LO category and installations with response >(2x-10%) in the HI category. The soil and site properties of all installations were thus associated with classes of response.

Identifying soil and site properties associated with LO and HI response are important, because landowners are interested in identifying areas with potential for high response. An intermediate analysis examined the effect of omitting the AVE

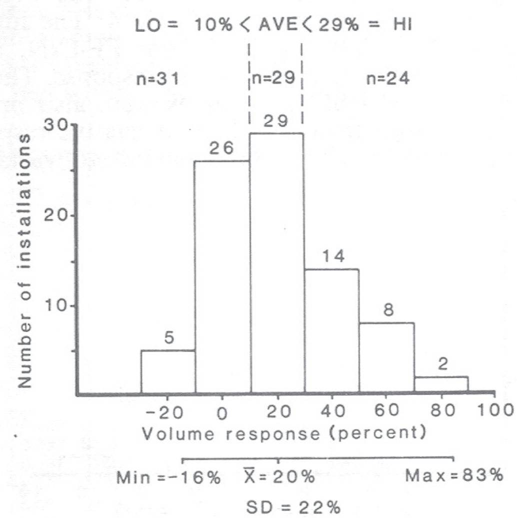

Fig. 3—Unthinned Douglas-fir observed 6-yr relative volume increment response to 448 kg of N^{-1} treatment; low (LO), average (AVE), and high (HI ≥ $2\bar{x}$ − 10%) response categories are depicted.

category (10% < AVE < 2×-10%); however, this AVE class of information was included for final analysis.

RESULTS

The intercorrelations between site index, forest floor properties, and surface soil properties of unfertilized unthinned plots within unthinned and thinned Douglas-fir stands are presented in Tables 2 and 3, respectively. Tables 4 to 6 contain correlation results of growth response with site index and soil properties. For each expression of response, variables associated with the three highest correlation coefficients are listed. All correlation coefficients presented are significant at the a=0.05 level, unless otherwise noted.

Correlations Between Soil Site Variables

Site index (SITE) has few significant correlations with the forest soil variables, with the highest being -0.43 (SS-C/N) for unthinned stands and -0.61 (SS-AVS) for thinned stands. The only forest floor variable significantly correlated with SITE is FF-C/N (r = -0.23) for unthinned stands (Table 2).

Forest floor total weight (FF-TW) of unthinned stands was significantly correlated with all forest floor carbon and nitrogen variables except FF-C/N (Table 2). This latter variable had its highest correlation with FF %N (r=0.66). A number of forest floor and surface soil properties were correlated with FF-%N is unthinned and thinned stands. Surface soil carbon (%) and SS-%N both have high positive correlations with SS CEC, indicating the importance of organic matter as exchange sites in surface horizons of these forest soils. The exchange properties of the surface soil (e.g., SS-CEC, SS-Ca, SS-BSAT) were significantly intercorrelated in both types of Douglas-fir stands.

Unthinned Douglas-fir Basal Area Response

Correlations with unthinned basal area PAI response to urea N are given in Table 4. The highest correlation with response was from FF-C/N, independent of sample or expression of response. The SS-C/N, FF-%N, and SITE variables were also prominent. The change from absolute to relative response altered the ranking of secondary and tertiary variables.

Estimating response had little effect in changing the order of the top three variables entering under observed response. Site index (SITE) generally became the secondary variable when changing from absolute to relative response, except under 448N response in the reduced (LO+HI) sample. The main effect of omitting the AVE response group was an increase in the magnitude of correlation coefficients.

Unthinned Douglas-fir Volume Response

Correlations with volume PAI response are given in Table 5. The highest correlation coefficients are again with FF-C/N. The frequency of SITE, C/N, and %N as highly correlated with volume response was similar to basal area PAI results in Table 4. In fact, for 448N response, the rankings are relatively unaffected by absolute, relative, observed, or estimated expressions of response, or even by thte reduction in sample size (omitting AVE class). The effect of sample size appears only to result in higher r values. The r values also increase with relative rather than absolute response, and for 224N response, a relative expression usually results in a change of secondary and tertiary variables. The entire array of forest soil variables is filled primarily with FF-C/N, SS-C/N, SITE, and SS%N; SS AVS and SS TOTP appear only under observed absolute response to 224N. The r values for comparable variables are also higher under 448N response compared with 224N response treatment level for each expression of response considered. The C/N ratio of the forest floor had the highest correlation in all cases.

Thinned Douglas-fir Volume Response

Correlations with volume PAI response to urea N in thinned installations are presented in Table 6. Relative response was always best correlated with FF-C/ N, whereas absolute response generally had the highest correlation with FF-N. The only surface soil variable ranked in Table 6 is SS-EXK; although it was ranked only once in the LO+AVE+HI) data, it occurred four times in the (LO+HI) data.

The r values among similar variables were higher for growth response in thinned stands (Table 6) than in unthinned stands (Table 5). However, omitting the AVE group in Table 6 greatly

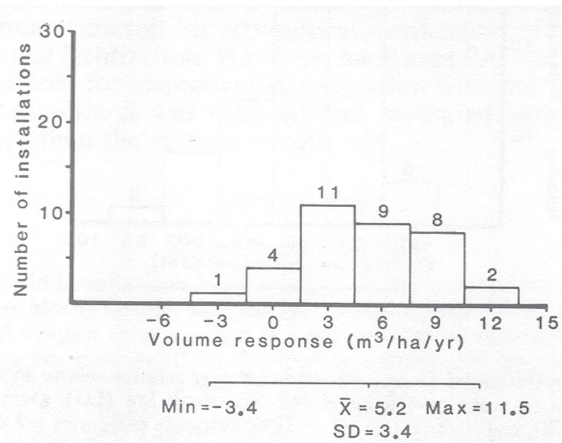

Fig. 4—Thinned Douglas-fir observed 6-yr absolute volume increment response to 448 kg of N ha^{-1} treatment.

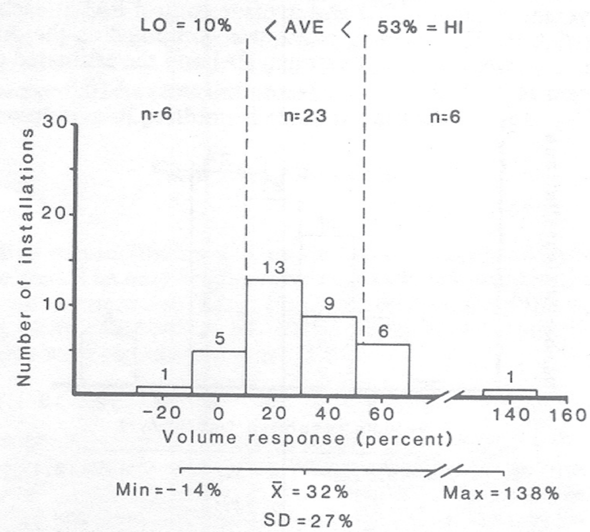

Fig. 5—Thinned Douglas-fir observed 6-yr relative volume increment response to 448 kg N/ha^{-1} treatment; low (LO), average (AVE), and high (HI ≥ $2\bar{x}$ − 10%) response categories are depicted.

Table 2—Correlation coefficients (*r*) between soil-site variables measured from unthinned stands ($n = 84$).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. SITE†	—																	
2. FF-TW	0.02	—																
3. FF-%N	0.09	−0.35*	—															
4. FF-N	0.02	0.82*	0.13	—														
5. FF-%C	−0.14	−0.36*	0.59*	−0.06	—													
6. FF-C	−0.03	0.90*	−0.14	0.88*	−0.03	—												
7. FF-C/N	−0.23*	0.10	−0.66*	−0.21	0.21	0.16	—											
8. SS-%N	0.11	−0.16	0.52*	0.05	0.25*	−0.12	−0.37*	—										
9. SS-%C	−0.05	−0.16	0.46*	0.02	0.37*	−0.08	−0.19	0.93*	—									
10. SS-PH	−0.23*	0.08	−0.19	0.06	−0.35*	−0.03	−0.10	−0.30*	−0.42*	—								
11. SS-EXCA	−0.26*	−0.02	−0.16	−0.07	−0.20	−0.12	−0.01	−0.19	−0.24*	0.70*	—							
12. SS-EXMG	0.08	−0.07	−0.18	−0.17	−0.26*	−0.21	−0.02	0.00	−0.12	0.31*	0.68*	—						
13. SS-EXK	−0.18	−0.01	−0.11	−0.01	−0.11	−0.07	0.04	0.04	−0.02	0.61*	0.78*	0.70*	—					
14. SS-CEC	0.14	−0.21	0.36*	−0.07	0.22	−0.19	−0.19	0.81*	0.75*	−0.17	0.04	0.32*	0.32*	—				
15. SS-AVP	−0.06	0.04	−0.14	−0.01	0.02	0.07	0.19	−0.27*	−0.25*	0.14	0.14	−0.09	0.00	−0.39*	—			
16. SS-TOTP	−0.08	−0.12	0.20	−0.04	0.21	−0.04	−0.01	0.44*	0.41*	0.08	−0.02	−0.06	0.16	0.38*	0.41*	—		
17. SS-AVS	−0.15	−0.16	0.23*	−0.07	0.15	−0.13	−0.11	0.33*	0.41*	−0.27*	−0.03	−0.10	−0.12	0.05	0.23*	0.02	—	
18. SS-BSAT	−0.23*	0.03	−0.23*	−0.06	−0.29*	−0.08	−0.91	−0.43*	−0.49*	0.69*	0.85*	0.53*	0.58*	−0.36*	0.28*	−0.19	0.05	—
19. SS-C/N	−0.43*	0.08	−0.19	0.01	0.29*	0.21	0.51*	−0.37*	−0.03	−0.16	−0.09	−0.29*	−0.19	−0.32*	0.15	−0.18	0.07	−0.03

* Denotes significance at $p \leq 0.05$.
† Site index, base age 50 y.

affected the correlations in all categories, and only 2 significant correlations were observed for 224 kg of N differences. When the entire sample is used, the correlation coefficients for a given variable are higher under 448N compared with 224N (also true for volume response in unthinned stands).

DISCUSSION

The larger sample size for unthinned installations (n=84) enabled stratification into LO, AVE, and HI categories without much effect on correlation coefficients. That is, there was no clustering effect–*a* situation where only a few points strongly influence the correlation. The sample of thinned installations (n=35) appears too small to use only LO+HI categories since the sample reduction greatly affected the number of significant correlations and the magnitude of individual correlation coefficients. On the other hand, we recognize that the importance of a responsesoils relationship may lie in the extremes (LO and HI),whereby the removal of the AVE class could be viewed as removing a masking element rather than simply inflating the correlation coefficients (such may be the case for SS-EXK in thinned stands).

Response in unthinned plots was consistently correlated with FF-C/N, followed by SS-C/N. Both of these properties are inversely related to (i) organic matter decomposition (Richards, 1974) and (ii) mineral nitrogen available for plant uptake (Powers, 1980). Carbon to nitrogen ratios in the Douglas-fir region of the Pacific Northwest vary from 17 to 67 for forest floors and 9 to 49 for mineral soils (Heilman, 1981). The range in FF-C/N and SS-C/N over all Douglasfir installations in this study was 27 to 57 and 16 to 44, respectively (Table 1). This was considered a representative sample of the large C/N ratio range over the Douglas-fir region and thus should include variation in nitrogen availability. Richards (1974) and Heilman (1981) have stated that mineral soil C/N ratios > 25 to 30 indicate immobilization of N by microbiota and therefore low nitrogen availability to plants. Other than the work of Turner (1977), who manipulated C/N ratios to extreme values, there is a lack of research on effects of forest floor C/N ratios on regulating nitrogen availability to Douglas-fir.

Total nitrogen concentration (%) in forest floor or surface soils and site index were frequently well correlated with growth response at unthinned installations. However, site index was absent in response analysis of thinned installations.

Fertilizer response correlations in thinned installations had slightly less consistency with forest floor and surface soil properties than in unthinned installations. However, the correlation coefficients were uniformly higher for growth response in thinned installations. Forest floor variables were generally those best correlated with growth response. Also, weights of

Table 3—Correlation coefficients (r) between soil-site variables measured from thinned stands ($n = 35$).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. SITE†	—																	
2. FF-TW	0.08	—																
3. FF-%N	0.27	0.14	—															
4. FF-N	0.15	0.95*	0.41*	—														
5. FF-%C	0.09	−0.27	0.60*	−0.09	—													
6. FF-C	0.17	0.91*	0.38*	0.93*	0.12	—												
7. FF-C/N	−0.17	−0.41*	−0.54*	−0.54*	0.33*	−0.27	—											
8. SS-%N	0.45*	−0.17	0.41*	−0.03	0.32	−0.05	−0.13	—										
9. SS-%C	0.25	−0.30	0.37*	−0.16	0.61*	−0.07	0.20	0.86*	—									
10. SS-PH	−0.31	0.14	−0.28	0.07	−0.47*	−0.06	−0.20	−0.34*	−0.51*	—								
11. SS-EXCA	−0.40*	0.05	−0.28	−0.05	−0.24	−0.09	0.02	−0.25	−0.33*	0.72*	—							
12. SS-EXMG	0.13	−0.14	−0.19	−0.20	−0.10	−0.23	0.08	0.16	0.00	0.38*	0.70*	—						
13. SS-EXK	−0.06	−0.19	−0.22	−0.25	−0.21	−0.31	0.02	−0.03	−0.16	0.39*	0.65*	0.76*	—					
14. SS-CEC	0.35*	−0.26	0.26	−0.14	0.29	−0.16	−0.01	0.79*	0.70*	−0.13	0.06	0.46*	0.40*	—				
15. SS-AVP	−0.27	−0.02	0.06	−0.01	0.02	−0.08	−0.05	−0.18	−0.08	0.07	0.13	−0.15	0.07	−0.27*	—			
16. SS-TOTP	0.04	−0.26	0.10	−0.20	0.19	−0.22	0.10	0.44	0.49*	−0.02	−0.01	0.10	0.25	0.43*	0.51*	—		
17. SS-AVS	−0.61*	−0.12	−0.04	−0.14	0.11	−0.13	0.09	0.11	0.27	−0.04	−0.19	−0.04	−0.10	−0.02	0.16	0.04	—	
18. SS-BSAT	−0.47*	0.14	−0.41*	−0.02	−0.47*	−0.09	−0.06	−0.51*	−0.62*	0.76*	0.89*	0.49*	0.46*	−0.33*	0.24	−0.17	0.19	—
19. SS-C/N	−0.35*	−0.21	−0.12	−0.23	0.44*	−0.03	0.56*	−0.51*	−0.05	−0.30	−0.22	−0.45*	−0.30*	−0.45*	0.21	−0.13	0.12	−0.13

* Denotes significance at $p \leq 0.05$.
† Site index, base age 50 y.

Table 4. The three soil and site properties having highest correlations (*r*) with classifications of unthinned basal area (PAI) response.

Response to 224 kg of N ha⁻¹				Response to 448 kg of N ha⁻¹			
Observed		Estimated		Observed		Estimated	
Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.
(LO + AVE + HI)† Installations							
FF-C/N (0.45)	FF-C/N (0.45)	FF-C/N (0.51)	FF-C/N (0.51)	FF-C/N (0.44)	FF-C/N (0.42)	FF-C/N (0.42)	FF-C/N (0.43)
FF-%N (−0.34)	SITE (−0.35)	SS-C/N (0.36)	SITE (−0.44)	SS-C/N (0.32)	SITE (−0.36)	SS-C/N (0.38)	SITE (−0.38)
SS-C/N (0.43)	FF-%N (−0.32)	FF-%N (−0.35)	FF-%N (−0.32)	FF-%N (−0.29)	FF-%N (−0.29)	SS-%N (−0.29)	SS-C/N (0.35)
(LO + HI)‡ Installations							
FF-C/N (0.48)	FF-C/N (0.49)	FF-C/N (0.56)	FF-C/N (0.58)	FF-C/N (0.53)	FF-C/N (0.55)	FF-C/N (0.47)	FF-C/N (0.54)
FF-%N (−0.36)	SITE (−0.42)	FF-%N (−0.48)	SITE (−0.48)	FF-%N (−0.42)	FF-%N (−0.41)	SS-C/N (0.43)	SS-C/N (0.46)
SS-C/N (0.33)	FF-%N (−0.37)	SS-C/N (0.46)	FF-%N (−0.44)	SITE (−0.33)	SITE (−0.39)	FF-%N (−0.39)	SITE (−0.42)

† (LO + AVE + HI) = 84 installations used in sample.
‡ (LO + HI) = 37–61 installations used in the sample.

Table 5—The three soil and site properties having highest correlations (*r*) with classifications of unthinned volume (PAI) response.

Response of 224 kg of N ha⁻¹				Response to 448 kg of N ha⁻¹			
Observed		Estimated		Observed		Estimated	
Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.
(LO + AVE + HI)† Installations							
FF-C/N (0.34)	FF-C/N (0.39)	FF-C/N (0.41)	FF-C/N (0.45)	FF-C/N (0.46)	FF-C/N (0.48)	FF-C/N (0.41)	FF-C/N (0.43)
SS-AVS (−0.26)	SITE (−0.32)	SS-C/N (−0.28)	SITE (0.36)	SS-C/N (0.39)	SS-C/N (0.41)	SS-C/N (0.41)	SS-C/N (0.43)
SS-TOTP (0.22)	SS-C/N (0.30)	SS-%N (−0.25)	SS-C/N (0.32)	SITE (−0.26)	SITE (−0.39)	SS-%N (−0.29)	SITE (−0.38)
(LO + HI)‡ Installations							
FF-C/N (0.40)	FF-C/N (0.44)	FF-C/N (0.44)	FF-C/N (0.51)	FF-C/N (0.52)	FF-C/N (0.53)	FF-C/N (0.47)	FF-C/N (0.47)
SS-AVS (−0.31)	SITE (−0.39)	SS-C/N (0.33)	SITE (−0.43)	SS-C/N (0.48)	SS-C/N (0.48)	SS-C/N (0.44)	SS-C/N (0.46)
SS-TOTP (0.28)	SS-C/N (0.35)	SS-%N (−0.30)	SS-C/N (0.38)	SITE (−0.40)	SITE (−0.47)	SITE (−0.32)	SITE (−0.41)

† (LO + AVE + HI) = 84 installations used in the sample.
‡ (LO + HI) = 37–61 installations used in the sample.

Table 6—The three soil and site properties having highest correlations (r) with classifications of thinned volume (PAI) response.

Response to 224 kg of N ha⁻¹				Response to 448 kg of N ha⁻¹			
Observed		Estimated		Observed		Estimated	
Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.
(LO + AVE + HI)† Installations							
FF-N (−0.49)	FF-C/N (0.58)	FF-N (−0.52)	FF-C/N (0.59)	FF-C/N (0.61)	FF-C/N (0.69)	FF-N (−0.57)	FF-C/N (0.62)
FF-C/N (0.46)	FF-N (−0.44)	FF-TW (−0.49)	FF-N (−0.49)	FF-N (−0.58)	FF-%N (−0.55)	FF-C/N (0.53)	FF-N (−0.54)
FF-TW (−0.43)	FF-%N (−0.43)	FF-C/N (0.48)	FF-TW (−0.42)	FF-TW (−0.49)	FF-N (−0.53)	SS-EXK (0.48)	FF-%N (−0.52)
(LO + HI)‡ Installations							
FF-C/N (0.83)	FF-C/N (0.76)	SS-EXK (0.65)	FF-C/N (0.70)	FF-C/N (0.78)	FF-%N (−0.87)	SS-EXK (0.83)	FF-%N (−0.84)
FF-%N (−0.62)	FF-%N (−0.69)	FF-C/N (0.65)	SS-EXK (0.62)	FF-N (−0.73)	FF-C/N (0.80)	FF-C (−0.72)	FF-C/N (0.76)
NS§	NS	FF-N (−0.60)	FF-%N (−0.59)	FF-%N (−0.70)	FF-N (−0.65)	FF-N (−0.71)	SS-EXK (0.73)

† (LO + AVE + HI) = 35 installations used in the sample.
‡ (LO + HI) = 8–14 installations used in the sample.
§ NS = No other properties had significant correlations with response at $P \leq 0.05$ level.

forest floor and forest floor N and C (e.g., FF-N, FF-C, and FF-TW, in kg ha ‘) were generally well correlated with response; this was not the case for unthinned stands. This result could be related to accelerated decomposition and mineralization after thinning due to increased soil surface temperatures or soil moisture regimes (Wollum and Schubert, 1975; Piene and Van Cleve, 1978; Piene, 1978). Addition of urea would further stimulate mineralization processes by reducing the C/N ratios of the forest floor and surface soils. In the case where forest floor C/N ratios were very high or forest floor total N (kg ha^{-1}) were low, the effect of thinning may be diminished or may even cause immobilization of nitrogen and carbon for a variable period of time (Cochran, 1968). Addition of urea to these stands would result in reduced C/N ratios of surface organic matter and thus promote accelerated decomposition and mineralization processes. These installations should be in the HI response category. Installations with initially low C/N ratios and/or higher total N weights of the forest floor would have good N mineralization rates in the untreated state so that neither thinning nor fertilization with urea would produce a significant response. These installations should be in the LO response category.

The consistent relationships found between Douglas-fir response (however measured) to urea fertilization and forest floor C/N ratios of the unfertilized stands encourages further investigation of factors regulating organic matter deocmposition and nitrogen availability in the Douglas-fir region soils. Of specific interest is the relationship between forest floor C/N ratio (and other related properties such as lignin content) and mineralizable N of the forest floor and surface soils (Shumway and Atkinson, 1978; Powers, 1980).

In reference to the possible relationship between SSEXK and thinned response, Piene and Van Cleve (1978) showed that potassium was the element released the quickest from decomposing organic matter in thinned white spruce stands in interior Alaska. Urea hydrolysis and leaching also have the potential of stripping exchangeable cations in the surface soil horizon (Cole et al., 1975). Johnson et al. (1982, p. 218) reviewed International Biological Program (IBP) data for the Douglas-fir region and concluded that due to intensive management practices there was a potential for potassium deficiency occurring in future rotations especially “where exchangeable potassium appears to be at a minimal level to meet uptake requirements and in view of the fact that weathering is apparently not keeping pace with uptake and leaching.” Although exchangeable potassium may underestimate “available” potassium for tree growth (Thompson et al. 1977), the correlation results indicate that the response of thinned Douglas-fir to urea may be limited in stands with low exchangeable K in surface soils (SS-EXK). This hypothesis requires further investigation.

CONCLUSIONS

The method of response classification used in this study has illustrated how sample size and initial stand conditions (unthinned or thinned) might affect both the properties correlated with growth response and the magnitude of the correlation coefficients.

The correlation of site index, surface soil, and forest floor properties to various categories of urea fertilizer response of thinned and unthinned Douglas-fir stands has allowed the identification of (i) those soil properties consistently (independent of growth response expression) and significantly related to response and (ii) those soil properties whose correlations with response were affected when the stands were both fertilized and thinned. Nitrogen and carbon properties (primarily from the forest floor), were variables showing the highest correlations with response. Forest floor C/N ratio had the highest correlation with all measures of unthinned Douglas-fir response. Forest floor C/N ratio was also consistently correlated with thinned Douglas-fir response. In these latter stands, however, the high correlations of forest floor weight or total N (kg ha 1j) with response indicated a probable interaction between increased decomposition from thinning and urea fertilization.

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