Intermountain Forest Tree Nutrition Cooperative

Supplemental Report No. 1

January 1999

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ABSTRACT

Individual tree basal area increment models for nitrogen fertilized stands were developed using data from permanent research plots located throughout the Inland Northwest. Results show that tree size, stand density, habitat type, and rock type significantly interact to affect individual tree basal area growth response to nitrogen fertilization. Small trees with high basal area in larger trees growing on moist habitat types and all rock types, except meta-sedimentary, exhibited greater relative response than larger trees with low basal area in larger trees growing in the same stand. Further, small trees with high basal area in larger trees growing on dry sites or on meta-sedimentary rocks showed less relative response than larger trees with low basal area in larger trees. Incorporating the new equations into individual tree growth and yield simulators would provide better representation of N fertilization response differences within a stand.

INTRODUCTION

Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) is important in a wide range of forest types for a wide array of non-timber product uses, and also plays a critical role in local and regional economies as a raw material for wood and paper products in the Inland Northwest. Therefore, forest managers apply intermediate silvicultural treatments, such as cleaning, thinning, and fertilization, to Douglas-fir stands to achieve specific management goals.

In the Inland Northwest, forest fertilization research began in the early 1960's (Loewenstein and Pitkin 1963, Loewenstein and Pitkin 1971). Early work focused on growth response of grand fir (*Abies grandis* (Dougl.) Lindl.) and Douglas-fir stands to thinning and nitrogen fertilization in northern Idaho (Olson 1981, Scanlin and Loewenstein 1981, Shafii et al.1989).

Considerable research (Shafii et al.1989, Mika and Moore 1990, Shafii et al.1990, Stage et al. 1990, Mika and Vander Ploeg 1991, Moore et al.1991, Mika et al.1992, Moore et al.1994, Mital 1995, Avila 1997) has shown that nitrogen fertilization can significantly increase basal area or volume growth. Shafii et al. (1990) found that initial tree size and initial stand density produced significant interactions on an individual tree's basal area growth response to nitrogen fertilization. Furthermore, rock type proved to be an important factor affecting growth response to N fertilization (Mika et al. 1992, Mital 1995). Forest habitat type and rock type are now used to guide operational fertilization programs in the region (Moore et al. 1998). However, there are no published individual tree basal area growth models that relate fertilization response to habitat type (Daubenmire and Daubenmire 1968), rock type, stand attributes, and tree attributes. Therefore, the primary objective of this study was to develop an individual tree basal area growth model for quantifying tree's basal area growth response to fertilization treatments across habitat type and rock type that would also be compatible with growth simulation models used in the region (Wykoff 1990).

DATA

Data used in this study was obtained from Intermountain Forest Tree Nutrition Cooperative (IFTNC) study sites. The study area covers six geographic regions: northern Idaho, western Montana, central Idaho, northeast Oregon, central Washington, and northeast Washington. From 1980 to 1982, the IFTNC established 94 fertilizer trials (installations) in the region.

Installations were located in second-growth, even-aged, managed Douglas-fir stands. Most stands had been thinned 5 to12 years prior to establishment; a few stands were unthinned, but naturally well spaced. Stands were selected to represent a range of stand densities, tree ages and sizes, and site productivities. The stands are dominated by Douglas-fir. Other species contributing substantial basal area include ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), and grand fir (*Abies grandis*).

Each installation contains six square plots ranging from 0.1 to 0.2 ac in size. The plots each contain at least ten Douglas-fir sample trees and were selected to minimize among-plot variation in terrain, vegetation composition, tree stocking, and tree size. Plots were grouped into two blocks of three plots based on similarity of these features to further reduce variation. First, three fertilizer treatments—0, 200, and 400 lb./ac of nitrogen—were randomly assigned to the plots within each block. Nitrogen in the form of urea was applied in the late fall utilizing handheld spreaders. After six years, a variable number of plots were retreated at each installation. However, trees from these retreated plots are not included in the current analysis.

All live trees were measured for both height and diameter (to the nearest 0.01 in.) at the time of the first treatment. Every two years diameters were remeasured on all trees over a ten-year period, and any incidence of damage or mortality along with probable cause was noted. Only trees alive at the end of the ten-year period, a total of 5065 Douglas-fir trees located on 257 plots across 94 installations, were used in this analysis. Thus, each tree had an observed 10-year growth period. Distribution of plots and distribution of Douglas-fir trees by habitat type, rock type, and treatment at the beginning of the 10-year growth period are provided in Tables 1 and 2. Distribution of Douglas-fir trees by crown class is listed in Table 3. Furthermore, selected stand and tree attributes are summarized in Tables 4 and 5.

METHODS

Dependent Variable

In this study, the natural logarithm of 10-yr periodic change in squared diameter, *ln*(DDS), was defined as the dependent variable in the individual-tree basal area increment model (Wykoff 1990).

$$DDS = DIB10^2 - DIB^2 \qquad (1)$$

where:

DDS = 10-year periodic growth in squared diameter at breast height.

DIB10 = inside bark diameter at breast height 10 years after treatment.

DIB = inside bark diameter at breast height at the beginning of the growth period.

Independent Variables

The abbreviations and descriptions of discrete (dummy) and continuous variables considered in the analysis are shown in Tables 6 and 7, respectively. In the field, habitat type series (HAB) was specified at five levels: grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), Douglas-fir-2 (*Pseudotsuga menziesii* II), western redcedar (*Thuja Plicata*), and western hemlock (*Tsuga heterophylla*). Since there were limited observations within selected habitat types on some rock types, in our analysis HAB is specified at three levels: moist (including grand fir, western redcedar, and western hemlock habitat types), dry (Douglas-fir habitat types), and dry-2 (moist Douglas-fir-2 habitat types).

For the site variables, quadratic terms of SL and EL were considered in the analysis. Aspect was considered only in the interaction terms with slope: SL[*sin*(ASP)] and SL[*cos*(ASP)] (Stage 1976). For tree variables and stand variables, the quadratic term and logarithmic transformations of each variable were tested as well as the interaction terms between *ln*(DBH+1) and crown ratio and relative size variables.

Variable Subset Selection

Because of the nature of the independent variables, it is likely that there are very strong linear dependencies among six tree size variables, among four tree vigor variables, among nine overall stand density variables, and among thirty relative tree size variables. If dependencies exist, coefficient estimates tend to be inflated and may even have the incorrect sign, and predicted values may be unreasonable. Usual variable selection methods (see Myers 1986, Miller 1991), such as forward selection, backward elimination, and stepwise regression, may fail to recognize these dependencies. Therefore, multicollinearity diagnostics were considered in the stepwise regression.

In our stepwise regression procedure, the dummy variables are always kept in the model whether or not their coefficients are statistically significant. In dummy coding, the maximum variance inflation factor and condition number should be considered in determining which level for each dummy variable was not included in the model. In addition, both SL[*cos*(ASP)] and SL[*sin*(ASP)] were considered as a single variable. If either is added to the model or replaces one variable already in the model, the other will also be entered to the model whether or not its coefficient is statistically significant (Stage 1976). In biased regression analysis (see Hoerl and Kennard 1970, McDonald and Schwing 1973, Hocking 1976), the ridge trace is used to suggest variables for deletion and, as a result, the parameter estimates of variables in the model are expected to be more stable. We used this approach to assist in variable subset selection.

Interaction Term Selection

The interaction between any of the variables representing tree size effects or competitive effects in the model and any of the dummy variables is used to test for differential increments (changes in slope) associated with various levels of HAB, ROC, TRT, or CRC. Possible higher-order interactions are included to test for differential increments. We considered the interaction to be statistically significant if the mean square error decreased, all the p-values of the coefficients in the model remained little changed, the maximum variance inflation factor was less than 10, and the condition number was less than 10 when the interaction term was included in the model.

Regression Diagnostics

In the influential data analysis, many influence measures have been developed (see Belsley et al. 1980, Hocking 1983, Myers 1986, Weisberg 1985), but all depend on two basic building blocks, namely the externally Studentized residuals and the diagonal elements of the hat matrix. In this study, the Studentized residuals are used to detect possible outliers. The diagonal elements of the hat matrix are applied to identify the high-leverage candidates. The scaled changes in fit which depend on both the Studentized residuals and the diagonal elements of the hat matrix were used to recognize the influential cases.

In the assessment of model adequacy, many statistical methods have been developed to test the assumption of normality, homoscedasticity, and independence of the error based on various regression diagnostics (see Weisberg 1983, Wetherill 1986). In practice, the simplest and most informative method for assessing the fit is to look at the model graphically, using an assortment of plots that, taken together, reveal the strengths and weaknesses of the model. In our study the following graphical analyses were checked to evaluate the model: normal quantile plot of residuals, plot of residuals against fitted values, and plots of residuals against the predictor variables.

RESULTS

The final model selected had the following form:

$$\begin{aligned} \mathit{ln}(\mathrm{DDS}) = {} & b_0 + \mathrm{HAB} + \mathrm{ROC} + \mathrm{TRT} + \mathrm{CRC} + b_1\,(\mathrm{SL}/100) + b_2\,(\mathrm{SL}/100)[\mathit{sin}(\mathrm{ASP})] \\ & + b_3\,(\mathrm{SL}/100)[\mathit{cos}(\mathrm{ASP})] + b_4\,(\mathrm{EL}/10000)^2 + b_5\,\mathit{ln}(\mathrm{DBH}) \\ & + b_6\,\mathit{ln}(\mathrm{CR}/100) \times \mathrm{CRC} + b_7\,\mathrm{RHT}/\mathit{ln}(\mathrm{DBH}+1) + b_8\,\mathit{ln}(\mathrm{TPA}/100) \\ & + b_9\,(\mathrm{BAL}/100)/\mathit{ln}(\mathrm{DBH}+1) \times \mathrm{HAB} \times \mathrm{ROC} \times \mathrm{TRT} \qquad (2) \end{aligned}$$

Parameter estimates and variance inflation factors for the final model are listed in Table 8. All coefficients associated with the continuous variables were statistically significant and have appropriate signs in the context of a theoretical biological model (Wykoff 1990). The differential increment for crown classes was significant across $\mathit{ln}(\mathrm{CR}/100)$. The differential increment for all combinations of habitat type, rock type, and treatment was also significant across $(\mathrm{BAL}/100)/\mathit{ln}(\mathrm{DBH}+1)$. The coefficient of determination, R^2 for the model, was 0.818. The mean square error of the model was 0.358 and the coefficient of variation of the model was

12.0%. The maximum variance inflation factor and condition number were 10.3 and 8.1, respectively. According to the collinearity diagnostics, there were no severe multicollinearity problems among the predictor variables. A small subset of observations were identified as potential outliers or influential data, but no reason could be found to delete these observations as outliers or influential cases after checking the original data in question. The residual plots did not show any objectional trends and did not suggest any problems with the assumptions made in fitting the model. In addition, there were significant differences among various levels of habitat type, rock type, and treatment.

To quantify individual tree's response to nitrogen fertilization, the response ratio (R) (Stage et al. 1990) for basal area increment is defined as

$$\mathrm{R} = exp\{\widehat{[ln(\mathrm{DDS})]}_{\mathrm{F}}\} \;/\; exp\{\widehat{[ln(\mathrm{DDS})]}_{\mathrm{C}}\} \qquad (3)$$

where:

$\widehat{[ln(\mathrm{DDS})]}_{\mathrm{F}}$ = predicted value from the final model with TRT = 200 or 400 lb. N/ac

$\widehat{[ln(\mathrm{DDS})]}_{\mathrm{C}}$ = predicted value from the final model with TRT = control

Using a logarithmic transformation, this response model can be linearized. Because of the logarithmic transformation of the dependent variable, predicted values based on the final model were corrected using a correction factor suggested by Baskerville (1972). The resulting equation can be expressed as

$$ln(\mathrm{R}) = c_0 + c_1\,(\mathrm{BAL}/100)/ln(\mathrm{DBH}+1) \qquad (4)$$

where:

c_0 = difference between the intercepts for no treatment and any fertilizer treatment.

c_1 = difference between the coefficients associated with the $(\mathrm{BAL}/100)/ln(\mathrm{DBH}+1)$ terms in the final model for any fertilizer treatment and control by habitat type and rock type.

Coefficients, c_0 and c_1, by habitat type, rock type, and fertilizer treatment for the response model (Equation 4) are given in Table 9.

To evaluate the trends of the response ratio across tree diameter and basal area in larger trees than the subject tree, simulations were conducted under the following conditions: two nitrogen treatment levels (200 lb. N/ac and 400 lb. N/ac); two habitat types (moist and dry); five rock types (granite, basalt, sedimentary meta-sedimentary, and mixed); tree diameter varied from 3 to 30 inches and basal area in larger trees than the subject tree ranged from 0 to 300 ft^2/ac, both corresponding to their range in the overall data. In the interest of brevity, the simulation results are plotted on response surface graphs for the combinations of one treatment level (200 lb. N/ac), two habitat types (moist and dry), and four rock types (Figure 1).

Moist habitats produced relatively greater response than dry habitats across all rock types (Figure 1). In addition, the shape of response surface, i.e. the relative distribution of response between individual trees within stands, differs between moist and dry habitats. On moist sites the response surface is upward sweeping; trees of small diameter with high basal area in larger trees produced higher relative fertilization response than large diameter trees with low basal area in larger trees. Higher relative response does not necessarily translate into higher absolute basal area growth. The only exception to this response pattern for moist sites occurred for stands growing on meta-sedimentary rocks. The shape of the response surface for meta-sedimentary rocks was downward sloping; similar in shape to response surfaces derived on dry sites. Small trees with high BAL produced relatively less fertilization response than large trees with low BAL growing in the same stand on drier sites. Although not shown, response surfaces for the 400 lb.

N/ac treatment were similar to those for the 200 lb. treatment, with somewhat higher average relative response.

The average Douglas-fir fertilization response ratios for 10-year basal area increment by habitat type, rock type, and treatment based on the final model and data used in the analysis are provided in Table 10. With the exception of the sedimentary rock type, 400 lb./ac of nitrogen produced greater relative response than the 200 lb. N/ac treatment.

DISCUSSION

The results of this study are directly useful for quantifying nitrogen fertilizer response of individual Douglas-fir trees in the Inland Northwest. Equation (4) could be compatible with individual tree growth simulation models, such as Prognosis (Wykoff et al. 1982), commonly used to forecast growth and yield in the Inland Northwest. In fact our study substantially expands the work of Stage et al. (1990) by providing fertilization response estimates for various habitat type and rock type combinations. Alternatively, the parameters provided in Table 10 could be used as crude individual tree N fertilization response growth multipliers by those who do not use individual tree simulation models formulated similar to the Prognosis model.

Perhaps the most interesting results of our study are the quantitative insights into individual tree competitive relationships across a variety of moisture (i.e. habitat types) and mineral nutrient (i.e. rock types) environments provided in Figure 1. On moist sites, trees growing in subordinate crown positions, those of small diameter with high BAL (i.e. suppressed), produced larger relative response to N fertilization than did large diameter trees with low BAL (i.e. dominants). This suggests that competition for N was particularly acute for the suppressed trees since they exhibited the greatest relative response when additional N was supplied by fertilization. However, this response pattern was only evident on moist sites (figure 1). On drier sites, suppressed trees exhibited relatively less response than dominants across all rock types. Suppressed trees often showed response ratios less than 1.0, indicating that after fertilization they grew less than similar trees on unfertilized control plots. Dominant trees on dry sites showed positive response to N fertilization, although less than dominant trees on moist sites. After N deficiency was alleviated by fertilization, suppressed trees on moist sites appearantly had sufficient moisture available to allow these trees to increase their growth rate in response to increased N availability. On drier sites, lack of moisture likely inhibited fertilization growth response by the suppressed trees, and since the dominant trees on dry sites showed positive growth response, the suppressed trees competitive disadvantage may have increased after N fertilization.

The shape of the response surface for meta-sedimentary rocks associated with moist habitats is downward sloping similar to those for drier sites, but unlike any other moist habitat/rock type combination. We feel the absence of response to N fertilization by suppressed trees growing on meta-sedimentary rocks results from a ~~rock~~ lack of mineral nutrients such as potassium, phosphorus, and some micro-nutrients rather than moisture limitations as previously discussed for dries sites. We feel this explanation is plausible for two primary reasons: 1) soils occurring on the moist/meta-sedimentary sites have good physical properties with high moisture holding capacity (Mital 1995); 2) soils developed from meta-sedimentary rocks in this region are infertile, particularly with respect to potassium (Moore et al. 1998). Meta-sedimentary rocks are composed primarily of SiO_2 (~90 % by weight), with very low content of essential mineral nutrients. Sites with low potassium status showed significantly lower stand level response to N fertilization than those with good K status (Mika and Moore 1990).

Essentially all Douglas-fir stands in the Inland Northwest are deficient in nitrogen (Moore et al. 1991), but, as demonstrated in our study, the within-stand distribution of fertilization growth response among individual trees is influenced by the availability of other growth limiting resources. Our results suggest that site moisture and other nutrient availability are the factors that affect the different patterns of individual tree response among stands. Suppressed trees show the greatest relative differences in growth response to N fertilization, reflecting acute inter-tree competitive interactions for moisture, nitrogen, and other mineral nutrients. This finding leads to the following speculation: currently dominant trees are sampled for foliage analysis to assay a stand's nutrient status (Everard 1973); perhaps sampling suppressed trees for foliar analysis would be more diagnostic.

CONCLUSIONS

This study quantifies the interactions of tree size, stand density, habitat type, and rock type to predict individual tree basal area growth response to N fertilization. Suppressed trees growing on moist sites and soils derived from granite, basalt, sedimentary, and mixed (glacial) rock types showed relatively greater response to N fertilization than dominant trees in the same stand. Conversely, suppressed trees growing on drier sites or on soils derived from meta-sedimentary rocks exhibited relatively less fertilization response than dominants. The basal area increment predictive equations were formulated to be compatible with individual-tree-distance-independent simulation models. Incorporating these new equations into growth and yield simulators such as Prognosis would allow better representation of N fertilization effects on stand development dynamics.

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Table 1. Distribution of plots by habitat type, rock type, and treatment at the beginning of the 10-year growth period

Habitat Type	Rock Type	Treatment			
		Control	200 lb N/acre	400 lb N/acre	Total
Moist [A]	Granite	6	6	5	17
	Basalt	12	12	10	34
	Meta-sediment	12	9	10	31
	Sediment	6	4	6	16
	Mixed (Glacial till)	9	7	5	21
	Total	45	38	36	119
Dry [B]	Granite	9	7	7	23
	Basalt	21	14	15	50
	Meta-sediment	2	1	2	5
	Sediment	4	4	2	10
	Mixed (Glacial till)	14	11	14	39
	Total	50	37	40	127
Dry-2 [C]	Mixed (Glacial till)	4	3	4	11

[A] includes grand fir, western redcedar, and western hemlock habitat types.

[B] includes Douglas-fir habitat types.

[C] includes moist Douglas-fir-2 habitat types.

Table 2. Distribution of Douglas-fir trees by habitat type, rock type, and treatment at the beginning of the 10-year growth period

Habitat Type	Rock Type	Treatment			
		Control	200 lb N/acre	400 lb N/acre	Total
Moist [A]	Granite	121	116	94	331
	Basalt	226	255	165	646
	Meta-sediment	246	192	199	637
	Sediment	134	69	114	317
	Mixed (Glacial till)	214	140	102	456
	Total	941	772	674	2387
Dry [B]	Granite	150	117	122	389
	Basalt	414	259	261	934
	Meta-sediment	32	25	43	100
	Sediment	91	85	42	218
	Mixed (Glacial till)	289	199	286	774
	Total	976	685	754	2415
Dry-2 [C]	Mixed (Glacial till)	99	75	89	263

[A] includes grand fir, western redcedar, and western hemlock habitat types.

[B] includes Douglas-fir habitat types.

[C] includes moist Douglas-fir-2 habitat types.

Table 3. Distribution of Douglas-fir trees by crown class at the beginning of the 10-year growth period

Crown Class	Number of Trees
Suppressed	134
Intermediate	931
Dominant*	4000
Total	5065

* includes dominant and co-dominant crown classes

Table 4. Averages and ranges of stand attributes at the beginning of the 10-year growth period

Attribute	Mean	Std Dev	Minimum	Maximum
Slope (%)	24	17	0	85
Aspect (degrees)	177	120	0	357
Elevation (ft)	3610	899	1500	5900
Site index* (ft @ 50 yr)	63	10	43	91
Age (yr)	65	17	27	100
Number of trees (stem/ac)	263	120	85	810
Mean tree height (ft)	61.6	12.1	31.1	102.2
Top height (ft)	66.7	13.7	37.0	121.0
Basal area (ft^2/ac)	138	45	39	301
Crown competition factor**	155	47	52	304
Quadratic mean diameter (in.)	10.20	2.12	5.22	19.05

* Monserud (1984).

** Wykoff et al. (1982).

Table 5. Averages and ranges of Douglas-fir tree attributes at the beginning of the 10-year growth period

Attribute	Mean	Std Dev	Minimum	Maximum
Diameter at breast height (in.)	9.84	3.28	2.32	30.42
Total height (ft)	61.8	15.5	17.4	128.5
Crown ratio (%)	47	13	10	99

Table 6. Abbreviations and descriptions of discrete variables considered in the analysis

Variable	Description
HAB	<u>Habitat types</u>
GF	Moist grand fir, western redcedar, and western hemlock types
DF	Dry Douglas-fir types
DF2	Moist Douglas-fir-2 types
ROC	<u>Rock types</u>
GRA	Granite
BAS	Basalt
MET	Meta-sediment
SED	Sediment
MIX	Mixed
TRT	<u>Fertilizer treatment types at the initiation of the experiment</u>
FN4	400 lb. N/ac
FN2	200 lb. N/ac
FC	Control
CRC	<u>Crown class types</u>
DOM	Dominant or co-dominant
INT	Intermediate
SUP	Suppressed

Table 7. Abbreviations and descriptions of continuous variables considered in the analysis

Variable	Description
	Site variables
SL	Stand slope percent (%)
ASP	Stand aspect (degrees)
EL	Stand elevation (ft)
	Tree size variables
DBH	Tree diameter at breast height (in.)
H	Total tree height (ft)
	Tree vigor variable
CR	Tree crown ratio (i.e. ratio of live crown length to total tree height (%))
	Overall stand density variables
TPA	Number of trees per acre (stem/ac)
BA	Basal area per acre (ft^2/ac)
CCF	Crown competition factor (Wykoff et al. 1982)
	Relative tree size variables
RBA	Ratio of the tree's basal area to the mean basal area on the plot
RH	Ratio of the tree's height to the mean height on the plot
RHD	Ratio of the tree's height to the mean height of dominant trees* on the plot
RCCF	Ratio of the tree's CCF to the mean CCF per tree on the plot (Shafii et al. 1990)
PCT	Basal area percentile rank of a tree (Stage 1973, Wykoff et al. 1982) (%)
BAL	Basal area in trees larger than the subject tree (Wykoff et al. 1982) (ft^2/ac)
NBAL	Basal area in trees with DBH larger than 90 percent of the subject tree's DBH (ft^2/ac)
CCFL	Crown competition factor in trees larger than the subject tree (Shafii et al. 1990)

* includes dominant and co-dominant trees

Table 8. Parameter estimates and variance inflation factors for the final model (Equation 2)

Variable			Parameter Estimate	Standard Error	P-value	VIF
Intercept	b_0		2.24612	0.11281	0.0001	0
HAB	DF		-0.31344	0.02028	0.0001	4.0654
	DF2		-0.21215	0.05107	0.0001	5.0864
	GF		0.00000	-	-	-
ROC	GR		0.16830	0.03327	0.0001	5.3462
	BA		0.04968	0.02539	0.0504	5.4801
	MS		0.11648	0.03190	0.0003	5.0127
	SE		-0.30948	0.03633	0.0001	4.9407
	MI		0.00000	-	-	-
TRT	C		-0.18434	0.02268	0.0001	4.8838
	F2		-0.09552	0.02383	0.0001	4.7450
	F4		0.00000	-	-	-
CRC	SUP		-0.39357	0.10051	0.0001	10.3073
	INT		0.19118	0.04076	0.0001	9.8762
	DOM		0.00000	-	-	-
SL/100	b_1		-0.08107	0.03580	0.0236	1.5143
SL/100[sin(ASP)]	b_2		-0.00930	0.02684	0.7289	1.2925
SL/100[cos(ASP)]	b_3		-0.26664	0.03097	0.0001	1.4697
$(EL/10000)^2$	b_4		-1.79837	0.09825	0.0001	1.7276
ln(DBH)	b_5		0.91640	0.02740	0.0001	3.3955
ln(CR/100)×CRC	b_6	SUP	0.75733	0.06923	0.0001	9.1017
		INT	1.09876	0.03635	0.0001	7.8834
		DOM	0.58490	0.02512	0.0001	3.6305
RHT/*ln*(DBH+1)	b_7		0.61539	0.14314	0.0001	1.8431
ln(TPA/100)	b_8		-0.24005	0.01539	0.0001	1.6779
(BAL/100)/*ln*(DBH+1)×HAB×ROC×TRT	b_9	GF,GR, C	-0.91153	0.08629	0.0001	1.7154
		GF,GR, F2	-0.86265	0.08818	0.0001	1.7041
		GF,GR, F4	-1.10259	0.09605	0.0001	1.6456
		GF,BA, C	-1.09480	0.06989	0.0001	2.1414
		GF,BA, F2	-0.83737	0.07071	0.0001	2.2096
		GF,BA, F4	-0.87152	0.08094	0.0001	1.9347
		GF,MS, C	-0.78114	0.06959	0.0001	2.1519
		GF,MS, F2	-0.81080	0.06401	0.0001	2.0074
		GF,MS, F4	-0.63814	0.07572	0.0001	2.0286
		GF,SE, C	-0.83980	0.08493	0.0001	2.1905
		GF,SE, F2	0.18694	0.14381	0.1937	1.5921
		GF,SE, F4	-0.61615	0.11697	0.0001	2.0520
		GF,MI, C	-0.87846	0.08348	0.0001	2.0811
		GF,MI, F2	-0.63905	0.08977	0.0001	1.8218
		GF,MI, F4	-0.69200	0.11682	0.0001	1.5319
		GF,GR, C	-0.60129	0.09525	0.0001	1.7992
		DF,GR, F2	-0.69212	0.10022	0.0001	1.5818
		DF,GR, F4	-0.79301	0.09355	0.0001	1.6610
		DF,BA, C	-0.46579	0.06557	0.0001	2.6892
		DF,BA, F2	-0.60993	0.07203	0.0001	2.1678
		DF,BA, F4	-0.67897	0.08314	0.0001	2.0160
		DF,MS, C	-1.46145	0.22029	0.0001	1.1992
		DF,MS, F2	-1.96150	0.23334	0.0001	1.2073
		DF,MS, F4	-0.69855	0.12418	0.0001	1.3274
		DF,SE, C	-0.31064	0.11074	0.0050	1.8170
		DF,SE, F2	-0.19368	0.11354	0.0881	1.8390
		DF,SE, F4	-0.53727	0.15345	0.0005	1.4167
		DF,MI, C	-0.86647	0.07798	0.0001	2.2650
		DF,MI, F2	-0.93509	0.08924	0.0001	1.9175
		DF,MI, F4	-0.84191	0.07927	0.0001	2.3280
		DF2, MI, C	-0.93938	0.17009	0.0001	2.3657
		DF2, MI, F2	-0.41493	0.16777	0.0134	2.0881
		DF2, MI, F4	-0.26413	0.16236	0.1038	2.2528

Table 9. Coefficients for the response model (Equation 4) by habitat type, rock type, and treatment

Habitat Type	Rock Type	Treatment			
		200 lb N/ac		400 lb N/ac	
		c_0	c_1	c_0	c_1
Moist [A]	Granite	0.08882	0.04888	0.18434	-0.19106
	Basalt	0.08882	0.25743	0.18434	0.22328
	Meta-sediment	0.08882	-0.02966	0.18434	0.14300
	Sediment	0.08882	1.02674	0.18434	0.22365
	Mixed (Glacial till)	0.08882	0.23941	0.18434	0.18647
Dry [B]	Granite	0.08882	-0.09083	0.18434	-0.19172
	Basalt	0.08882	-0.14414	0.18434	-0.21318
	Meta-sediment	0.08882	-0.50004	0.18434	0.76290
	Sediment	0.08882	0.11697	0.18434	-0.22663
	Mixed (Glacial till)	0.08882	-0.06862	0.18434	0.02456
Dry-2 [C]	Mixed (Glacial till)	0.08882	0.52446	0.18434	0.67525

[A] includes grand fir, western redcedar, and western hemlock habitat types.

[B] includes Douglas-fir habitat types.

[C] includes moist Douglas-fir-2 habitat types.

Table 10. Average response ratios for basal area increment by habitat type, rock type, and treatment based on the final model (Equation 2)

Habitat Type	Rock Type	Treatment	
		200 lb N/ac	400 lb N/ac
Moist [A]	Granite	1.10760	1.14240
	Basalt	1.17037	1.27582
	Meta-sediment	1.08353	1.25403
	Sediment	1.49383	1.28219
	Mixed (Glacial till)	1.15629	1.25622
Dry [B]	Granite	1.06683	1.14320
	Basalt	1.05445	1.14073
	Meta-sediment	0.98810	1.42184
	Sediment	1.13071	1.12755
	Mixed (Glacial till)	1.07454	1.20978
Dry-2 [C]	Mixed (Glacial till)	1.23978	1.41630

[A] includes grand fir, western redcedar, and western hemlock habitat types.

[B] includes Douglas-fir habitat types.

[C] includes moist Douglas-fir-2 habitat types.

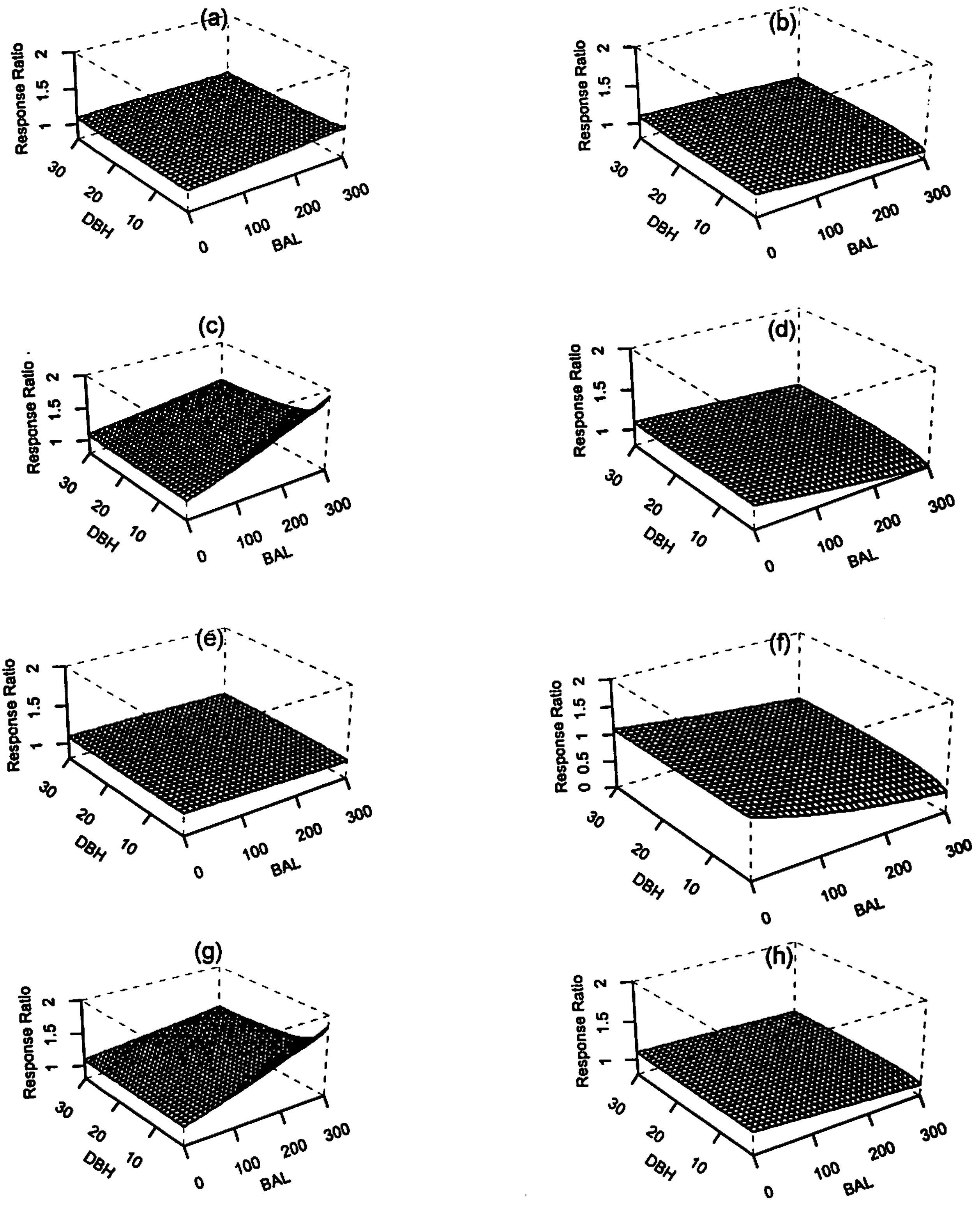

Figure 1. Response ratio to the 200 lb. N/ac treatment for basal area increment (Equation 4) depends on tree diameter, basal area in trees larger than the subject tree, habitat type, and rock type: (a) moist/granite, (b) dry/granite, (c) moist/basalt, (d) dry/basalt, (e) moist/meta-sediment, (f) dry/meta-sediment, (g) moist/mixed, (h) dry/mixed.