Individual-tree diameter growth models for quantifying within-stand response to nitrogen fertilization[1]

BAHMAN SHAFII
Agricultural Experiment Station, College of Agriculture, University of Idaho, Moscow, ID 83843, U.S.A.
JAMES A. MOORE
College of Forestry, Wildlife and Range Sciences, University of Idaho, Moscow, ID 83843, U.S.A.
AND
JAMES D. NEWBERRY
Potlatch Corporation, Lewiston, ID 83501, U.S.A.

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Diameter-increment models for nitrogen-fertilized stands were developed using data from permanent research plots in northern Idaho. The equations partially resembled PROGNOSIS model diameter growth formulations. Results indicated that both initial tree size and initial stand density produced significant interactions with treatment to explain an individual tree's response to fertilization. Larger trees in a stand showed more fertilization response than smaller trees. Furthermore, individual trees in low-density stands showed more fertilization response than those growing in high-density stands. These diameter increment predictive equations were formulated to be compatible with individual-tree distance-independent simulation models.

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Des modèles d'accroissement en diamètre ont été développés pour des peuplements fertilisés en utilisant des données de parcelles permanentes de recherche situées dans le nord de l'Idaho. Les équations ressemblent partiellement aux modèles de croissance en diamètre de PROGNOSIS. Les résultats indiquent que la taille initiale de l'arbre et la densité initiale du peuplement produisent des interactions significatives avec le traitement pour expliquer les réponses individuelles des arbres à la fertilisation. Les plus gros arbres dans le peuplement montrent une réponse plus élevée que les plus petits. De plus, les arbres individuels dans les peuplements de faible densité ont montré une réponse à la fertilisation supérieure à ceux croissant dans les peuplements de forte densité. Ces équations de prédiction d'accroissement en diamètre ont été formulées pour être compatibles avec celles du modèle de simulation utilisant les arbres individuels sans prendre en considération la distance entre les arbres.

[Traduit par la revue]

Introduction

Growth models involving explicit prediction of yields in forest stands can generally be divided into two categories: stand-level and tree-level models. Recently, the use of the individual-tree, distance-independent (Munro 1974) growth models has been emphasized (e.g., PROGNOSIS, Wykoff *et al.* 1982; SPS, Arney 1985) in the Inland Northwest. Models of this form employ conventional-stand table data (along with some stand-level statistics) and can provide growth projections in stands with mixed size classes, age classes, and species. However, there are no published individual-tree fertilization diameter-growth prediction equations formulated to be compatible with these types of simulation models. Individual-tree analysis of fertilization response may also provide valuable insights into the effect of fertilization on stand dynamics. Thus, the primary objective of this study was to quantify within-stand variation of nitrogen fertilization response using existing individual-tree, distance-independent diameter-increment models as the basis for initial model formulation.

Source and description of data

The data set used in this study included 127 permanent plots on 21 installations (sites) throughout northern Idaho. Three independent research studies were used as data sources. These were (*i*) the University of Idaho McIntire-Stennis (MS-16) Study, (*ii*) the Forest Service, USDA, Intermountain Forest and Range Experiment Station, Intensive Timber Culture (ITC) Study, and (*iii*) a Potlatch Corporation thinning and fertilization study. Data sources were selected based upon the duration of post-treatment measurements and predominance (basal area $> 50\%$) of grand fir and Douglas-fir.

The MS-16 study supplied the largest data set with 13 installations containing a total of 91 plots. The fertilization and thinning experiments for this study were established in the early 1970s (Scanlin *et al.* 1978). These sites provided 14 years of post-treatment stem height and diameter measurements. Each installation contained eight, square 0.1 acre plots (1 acre = 0.4 ha). Four of the eight plots, selected at random, were thinned to approximately a 15 × 15 ft spacing and four were left unthinned (1 ft = 0.304 m). Thinning type and intensity varied both within and between installations. Since no prethinning records were available, actual thinning intensities were unknown. Urea nitrogen fertilizer was then applied randomly at the rate of 200 lb of N/acre (1 lb = 454 g) to two thinned and two unthinned plots, thereby providing two replicates of four treatments (a 2 × 2 factorial arrangement) within each installation; i.e., control(1), thinned only(2), fertilized only(3), and thinned and fertilized(4). Although originally eight plots at each site were considered, field evaluation of each site in 1985 resulted in the elimination of some plots from the study, owing to factors such as logging, road building, etc.

Five installations were obtained from the ITC study, containing a total of 12 plots. This study was established during 1974–1977

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TABLE 1. Distribution of selected mensurational characteristics according to the data sources

	Mean			SD			Minimum			Maximum		
	MS-16	ITC	Potlatch	MS-16	ITC	Potlatch	MS-16	ITC	Potlatch	MS-16	ITC	Potlatch
Breast height age* (years)	42	52	56	13	20	14	21	19	38	77	84	96
Site index† (ft, base age 50)	58	59	68	12	14	9	30	40	50	90	80	80
Crown ratio (%)	39	45	30	20	24	10	10	10	10	90	90	60
dbh (in.)	6.3	6.6	10.3	3.5	4.7	2.8	1.0	0.5	2.9	19.5	20.2	18.9
Height* (ft)	51	50	73	20	27	11	20	10	42	113	97	104
Basal area (ft/acre)	122	113	182	70	71	43	19	2	96	314	209	263
CCF‡	169	141	218	68	87	58	24	6	120	371	278	317

*Represents statistics on sample trees for which height–age measurements were recorded.
†Grand fir site index (Stage 1959).
‡Crown competition factor (Wykoff *et al.* 1982).

and included only thinned and thinned and fertilized plots. The plots were thinned and fertilized in a manner similar to the MS-16 plots. A combination of low thinning and spacing guidelines with the target spacing from 10 × 10 ft up to 15 × 15 ft was used for this study.

Potlatch Corporation experiments, established in the late 1970s, provided a third data set containing plots from seven installations with a range of fertilization treatment levels. However, only a subset of three installations, containing 24 plots with the same treatment arrangement as the MS-16 study, were included in this analysis. Six years of post-treatment growth measurements were available from these data. The square plot sizes varied from 0.1 to 0.25 acres. Various methods of thinning (i.e., mechanical, chemical, commercial) were used in these installations with spacing guidelines ranging from 12 × 12 to 15 × 15 ft.

Although all installations were permanent and periodically remeasured, the time since treatment and remeasurement interval varied. Thus, increment cores from a subset of trees were used to standardize growth periods across the data sets. From each data source, only trees with recorded annual increment cores were included in the analysis. One increment core was extracted from each sample tree from the side facing plot center. The annual radial increments were measured using a digital measuring system to ±0.01-mm resolution. Fourteen-, 10-, and 5-year periodic radial increments were then calculated from the annual increments. Radial increments were doubled to obtain diameter increments. Individual tree records were edited for species codes, tree age, initial diameter, condition codes, treatment codes, and unusual height and diameter increments. Errors detected were checked with the field data, corrected where necessary, or were the basis for rejecting the tree. The number of individual tree observations obtained from each of the data sources, MS-16, ITC, and Potlatch, were 1670, 209, and 538, respectively. The distribution of selected mensurational characteristics of the three data sources are given in Table 1. The study areas were second-growth even-aged stands composed primarily of grand fir and Douglas-fir species.

The MS-16 data were used to develop several diameter increment models. The ITC and Potlatch studies were used as independent test data sets. Diameter-increment models were constructed for growth periods of 14, 10, and 5 years. Based on the length of the growth period since treatment, observations from ITC and Potlatch sources were employed, accordingly, for 10- and 5-year model validation.

Analysis

PROGNOSIS is an individual-tree, distance-independent growth simulation model used extensively in the mixed-species types of the Inland Empire region. The diameter-increment model (a primary component of the simulator) used in PROGNOSIS has been proven to work well for forests in the region. Thus, a modified version of the PROGNOSIS diameter-increment model was used as the first attempt in quantifying the fertilization effect on diameter growth in thinned and unthinned stands.

The PROGNOSIS-type diameter-increment prediction model was specified as follows:

$$\begin{aligned}\text{DIS} = {} & \beta_0 + \text{HAB} + \text{TRT} + \text{SPCS} + \beta_1\text{CASP} \\ & + \beta_2\text{SASP} + \beta_3\text{SL} + \beta_4\text{SL}^2 + \beta_5\text{EL} \\ & + \beta_6\text{EL}^2 + \beta_7\text{CR} + \beta_8\text{CR}^2 + \beta_9(\text{CCF}_\text{L}/100) \\ & + \beta_{10}\text{RDBH} + \beta_{11}\text{LDBH} \times \text{TRT} \\ & + \beta_{12}(\text{BA}/100) \times \text{TRT}\end{aligned} \tag*{[1]}$$

where

DIS = ln(DDS), DDS represents squared inside-bark diameter growth, ln indicates the natural (base e) logarithm
β_0 = constant term representing the overall regression intercept
HAB = dummy variable representing habitat type (*Thuja plicata/Pachistima myrsinites* = WRC/P) (*Abies grandis/P. myrsinites* = GF/P)
TRT = dummy variable representing treatment type (control = C, fertilized = F, thinned = T, thinned and fertilized = F + T)
SPSC = dummy variable representing species (grand fir = GF, Douglas-fir = DF)
SL = stand slope percent
CASP = SL cos(ASP), ASP represents the stand aspect (deg.)
SASP = SL sin(ASP)
EL = stand elevation (in hundreds of feet)
CR = individual-tree percent live crown
CCF$_\text{L}$ = crown competition factor in trees larger than the subject tree
RDBH = relative dbh, defined as the initial dbh of subject tree divided by the average stand diameter (ASD)
BA = initial stand basal area (ft^2/acre)
LDBH = ln(dbh)
β_1–β_{12} = regression coefficients

TABLE 2. Estimated regression coefficients for the PROGNOSIS-type diameter increment model (eq. 1)

Variable		14-year			10-year			5-year		
		Coefficient	SEE	$P > \|t\|$	Coefficient	SEE	$P > \|t\|$	Coefficient	SEE	$P > \|t\|$
	β_0	−4.6401	1.6068	0.0039	−4.8252	1.6279	0.0031	−5.4375	1.6319	0.0009
HAB	WRC/P	0.1118	0.0549	0.0419	0.1567	0.0556	0.0050	0.2287	0.0557	0.0001
	GF/P	0.0000	—	—	0.0000	—	—	0.0000	—	—
TRT	C	−1.1094	0.1849	0.0001	−1.0423	0.1874	0.0001	−0.9496	0.1878	0.0001
	F	−0.9967	0.1751	0.0001	−0.9522	0.1774	0.0001	−0.8194	0.1778	0.0001
	T	−0.1076	0.1876	0.5662	0.0129	0.1900	0.9459	−0.1759	0.1905	0.3559
	F+T	0.0000	—	—	0.0000	—	—	0.0000	—	—
SPCS	GF	−0.0775	0.0503	0.1232	−0.0043	0.0509	0.9326	−0.0040	0.0511	0.9371
	DF	0.0000	—	—	0.0000	—	—	0.0000	—	—
CASP	β_1	0.0090	0.0017	0.0001	0.0082	0.0017	0.0001	0.0086	0.0017	0.0001
SASP	β_2	−0.0033	0.0014	0.0213	−0.0038	0.0014	0.0076	−0.0048	0.0014	0.0009
SL_2	β_3	0.0133	0.0059	0.0265	0.0162	0.0061	0.0076	0.0156	0.0060	0.0102
SL	β_4	−0.0002	0.0001	0.0584	0.0003	0.0001	0.0166	−0.0003	0.0001	0.0253
EL_2	β_5	0.2883	0.0882	0.0011	0.2500	0.0893	0.0052	0.2260	0.0895	0.0117
EL	β_6	−0.0043	0.0012	0.0005	−0.0037	0.0012	0.0035	−0.0034	0.0013	0.0072
CR_2	β_7	0.3526	0.0507	0.0001	0.3672	0.0514	0.0001	0.2882	0.0515	0.0001
CR	β_8	−0.0145	0.0055	0.0088	−0.0167	0.0056	0.0028	−0.0113	0.0056	0.0440
CCF_L	β_9	−0.5013	0.0621	0.0001	−0.5480	0.0628	0.0001	−0.4983	0.0630	0.0001
RDBH	β_{10}	0.1847	0.0695	0.0080	0.1666	0.0704	0.0181	0.1595	0.0705	0.0239
LDBH × TRT	C	0.8943	0.1256	0.0001	0.8915	0.1271	0.0001	0.7751	0.1274	0.0001
	F	0.8887	0.1234	0.0001	0.8857	0.1251	0.0001	0.8005	0.1254	0.0001
	T	0.5484	0.1166	0.0001	0.5251	0.1181	0.0001	0.6201	0.1184	0.0001
	T+F	0.6814	0.1369	0.0001	0.6291	0.1387	0.0001	0.7675	0.1391	0.0001
BA × TRT	C	−0.3914	0.1074	0.0003	−0.3766	0.1088	0.0006	−0.3522	0.1092	0.0013
	F	−0.2525	0.1073	0.0187	−0.2451	0.1087	0.0243	−0.2399	0.1089	0.0278
	T	−0.7029	0.1384	0.0001	−0.6215	0.1401	0.0001	−0.8079	0.1405	0.0001
	T+F	−0.7282	0.1806	0.0001	−0.5613	0.1829	0.0022	−0.8452	0.1834	0.0001

NOTE: SEE, standard error of estimates; $P > |t|$, probability of obtaining a larger $|t|$ under the hypothesis H_0: parameter = 0.

The diameter increment, as defined above, is derived from the periodic change in the squared inside-bark diameter (DDS), which is proportional to the periodic basal area growth:

$$\text{DDS} = (\text{DIB} + R)^2 - \text{DIB}^2 = 2\text{DIB} \times R + R^2$$

where

DIB = diameter inside-bark at the beginning of the growth period

R = periodic DIB increment

The model includes three dummy variables expressing the differential effects (direction of shift in the intercept as well as change in the slope) of habitat type, treatment, and species on DIS. HAB is specified at two levels: *A. grandis/P. myrsinites* and *T. plicata/P. myrsinites* (Daubenmire and Daubenmire 1968). TRT is specified at four levels: control, fertilized (200 lb N/acre), thinned, and thinned and fertilized. SPCS is specified at two levels: grand fir (*A. grandis* (Doug.) Lindl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco).

The site factors included in the model, i.e., slope, aspect, habitat type, and elevation, are the same as those given in the PROGNOSIS diameter-increment model specification. The specific expressions used to incorporate the effects of aspect, slope, and habitat type on tree growth are those suggested by Stage (1976). No attempt was made to consider other forms or alternate expressions for these variables.

The growth model also includes, as independent variables, a measure of stand density (BA), as well as two measures of relative competitive status (RDBH and CCF_L). Originally, three measures of stand density and five measures of competition were considered. The measures of stand density were basal area (BA), crown competition factor (CCF), and number of trees per acre (TPA). The measures of individual-tree competitive status were relative dbh (RDBH, defined as dbh of subject tree/ASD), relative basal area (RBA, defined as BA of subject tree/stand's average BA per tree), relative crown competition factor (RCCF, defined as CCF of subject tree/stand's average CCF per tree), basal area in larger trees (BA_L, defined as BA in trees larger than the subject tree; i.e., BA_L for the largest tree in the stand = 0, and BA_L for the smallest tree in the stand = accumulated sum of BA for all the other trees in the stand); and crown competition factor in larger trees (CCF_L, defined in the same manner as BA_L).

A stepwise regression procedure (backward elimination technique) was employed to select a subset of the aforementioned variables with the highest contribution to the model. The selection technique was performed only on the eight competition-related variables above, keeping the other site and tree variables as specified in the model. At each step, the density and (or) competition variable showing the smallest contribution to the model was deleted, until the remaining variables in the model (i.e., BA_L, RDBH, and CCF_L) produced F statistics significant at the $\alpha = 0.05$ level (Table 2).

TABLE 3. Estimated regression coefficients for the diameter-increment model (eq. 2)

Variable		14-year			10-year			5-year		
		Coefficient	SEE	$P > \lvert t \rvert$	Coefficient	SEE	$P > \lvert t \rvert$	Coefficient	SEE	$P > \lvert t \rvert$
	β_0	0.7580	0.2166	0.0005	−0.1505	0.2185	0.4191	−1.1704	0.2209	0.0001
TRT	C	−1.2939	0.1861	0.0001	−1.2001	0.1878	0.0001	−1.1056	0.1898	0.0001
	F	−1.0914	0.1790	0.0001	−1.0584	0.1806	0.0001	−0.9129	0.1827	0.0001
	T	−0.2343	0.1885	0.2140	−0.0916	0.1902	0.6300	−0.2803	0.1923	0.1452
	T+F	0.0000	—	—	0.0000	—	—	0.0000	—	—
SPCS	GF	−0.1893	0.0483	0.0001	−0.0851	0.0487	0.0806	−0.1134	0.0493	0.0217
	DF	0.0000	—	—	0.0000	—	—	0.0000	—	—
SI	β_1	0.0027	0.0016	0.0623	0.0447	0.0019	0.0189	0.0055	0.0020	0.0060
CR	β_2	0.3089	0.0485	0.0001	0.3388	0.0489	0.0001	0.2510	0.0494	0.0001
CR^2	β_3	−0.0145	0.0052	0.0055	−0.0168	0.0053	0.0015	−0.0108	0.0053	0.0429
CCF_L	β_4	−0.5509	0.0626	0.0001	−0.5818	0.0631	0.0001	−0.5257	0.0638	0.0001
RDBH	β_5	0.2654	0.0647	0.0001	0.2492	0.0653	0.0001	0.2336	0.0660	0.0004
LDBH × TRT	C	0.7816	0.1152	0.0001	0.7832	0.1163	0.0001	0.6979	0.1176	0.0001
	F	0.7397	0.1144	0.0001	0.7375	0.1154	0.0001	0.6762	0.1167	0.0001
	T	0.5716	0.1107	0.0001	0.5178	0.1117	0.0001	0.6563	0.1129	0.0001
	T+F	0.6308	0.1282	0.0001	0.5643	0.1293	0.0001	0.7523	0.1308	0.0001
BA+TRT	C	−0.5175	0.1069	0.0001	−0.5131	0.1079	0.0001	−0.5364	0.1091	0.0001
	F	−0.3774	0.1067	0.0004	−0.3556	0.1077	0.0010	−0.3962	0.1089	0.0003
	T	−1.1923	0.1246	0.0001	−1.0625	0.1257	0.0001	−1.3646	0.1271	0.0001
	T+F	−1.1911	0.1708	0.0001	−0.9765	0.1724	0.0001	−1.3885	0.1743	0.0001

The tree variable, LDBH, and the density variable, BA, are included in the model as interactions with treatment. Interactions were included to test for differential increments (changes in slope) associated with each treatment level. No other form or order of interactions, including those associated with species and site factors, were found to be statistically significant and were not included in the final model.

Since site index is a commonly used method for estimating site quality, a second diameter-increment model was formulated by replacing the seven site-dependent terms in [1] with the site index. Using the site index as the measure of site quality makes the model more parsimonious. This eliminates collinearity among the site factors and reduces the potential for ill conditioning between these and other regression variates in the model.

This diameter-increment model took the form

$$[2] \quad \text{DIS} = \beta_0 + \text{TRT} + \text{SPCS} + \beta_1\text{SI} + \beta_2\text{CR} + \beta_3\text{CR}^2 + \beta_4(\text{CCF}_\text{L}/100) + \beta_5\text{RDBH} + \beta_6\text{LDBH} \times \text{TRT} + \beta_7(\text{BA}/100) \times \text{TRT}$$

where SI = grand fir site index (feet at 50 years, breast height) and all the other terms are as previously defined. The same selection procedures and statistical criteria were used in deciding the density, competition, and appropriate interaction terms to be included in this model.

The grand fir site-index curves developed by Stage (1959) were used for grand fir stands, and for Douglas-fir stands, Monserud's (1985) equations were used. The appropriate conversion equations developed by Deitschman and Green (1965) were applied to estimate the grand fir site index. The use of eq. [2] depends on the availability of appropriate site-index equations and site trees. If site-index estimates are not available, then eq.[1] could be used.

Results and discussion

Regression results for models [1] and [2] were similar over the specified growth periods. All slope coefficients associated with the continuous variables were significant, and had comparable standard errors for all three growth periods. The R^2 values associated with eq. 1 for 14-, 10-, and 5-year growth periods were 0.71, 0.72, and 0.69, respectively. For eq. 2, the R^2 values were 0.70, 0.70, and 0.68 for the three growth periods. Residuals from both models showed no bias when displayed by all tree, density, and competition variables as well as the predicted value of DIS. Regression results for both diameter-increment models are provided in Tables 2 and 3. The results indicate an insignificant intercept effect for thinning treatment across all growth periods. However, the differential increment for all treatment combinations is highly significant across diameter and initial basal area for the specified growth periods. It is clear that thinning treatment has significantly affected individual tree basal-area increments across the diameter classes and initial density within the stands. The same is true for the fertilization treatments.

Because inclusion of SI in place of site factors given in eq. 1 did not substantially affect the overall fit and (or) the statistical significance of individual terms in the model, particularly with respect to fertilization, subsequent results and discussion will focus on eq. 2. However, there was one difference in the results the two models: the use of SI caused less variation to be accounted for by site factors and correspondingly more by density variables.

The behavior of the predicted diameter-increment model (14-year growth period; grand fir species) is shown in two-dimensional plots of DDS versus dbh and BA, Figs. 1 and 2, respectively. The values of other independent variables in each figure were held constant at their treatment means.

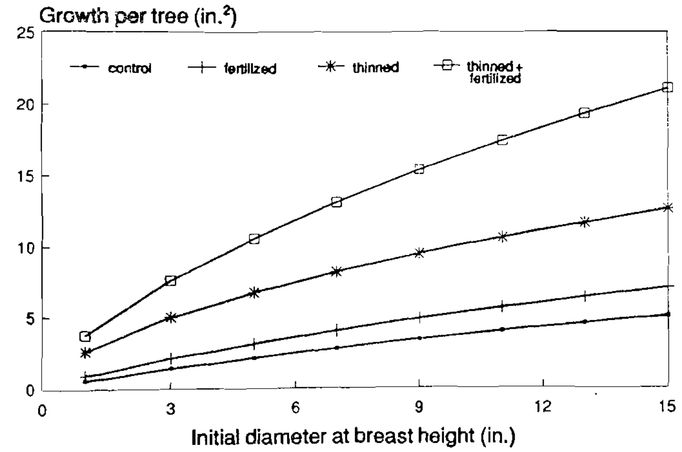

FIG. 1. Predicted 14-year individual-tree basal area increment versus initial diameter at breast height for grand fir.

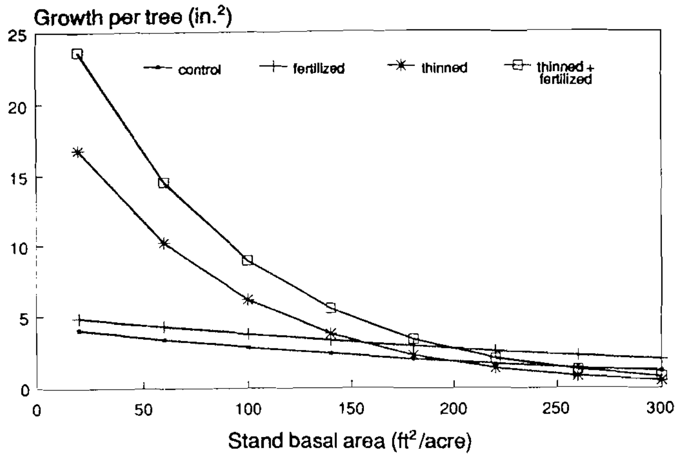

FIG. 2. Predicted 14-year individual-tree basal area increment versus initial basal area per acre for grand fir.

Because of the logarithmic transformation of the dependent variable, DIS, a correction factor suggested by Baskerville (1972) was used to account for the bias introduced in the predicted value of DIS as a result of the transformation.

The shape of the DDS curve relative to dbh for all treatment combinations is a monotonically increasing function with no apparent maximum within the range of the available data (see Table 1). The quadratic term $(\mathrm{LDBH})^2$ was not significant, probably because the data comprised only 8% of trees larger than 12 in. in diamter (1 in. = 2.54 cm).

The monotonically decreasing shape of the increment function in Fig. 2 indicates declining individual-tree diameter increment as the stand density (BA) increases. The position of the increment curves by treatment changes as stand density varies. This is consistent with the results given in Table 3, indicating significant interactions between BA and TRT levels. Tree diameter increment was higher for thinned stands of lower density ($\mathrm{BA} \leq 150$ ft²/acre). There was no treatment difference in tree diameter increment for higher stand densities. Thinning, as expected, results in the largest individual-tree diameter increments in lower stand densities. These results are consistent with those reported by Reukema and Bruce (1977) and Seidel (1987).

Individual tree response to nitrogen fertilization is illustrated in Fig. 3. Response is defined as

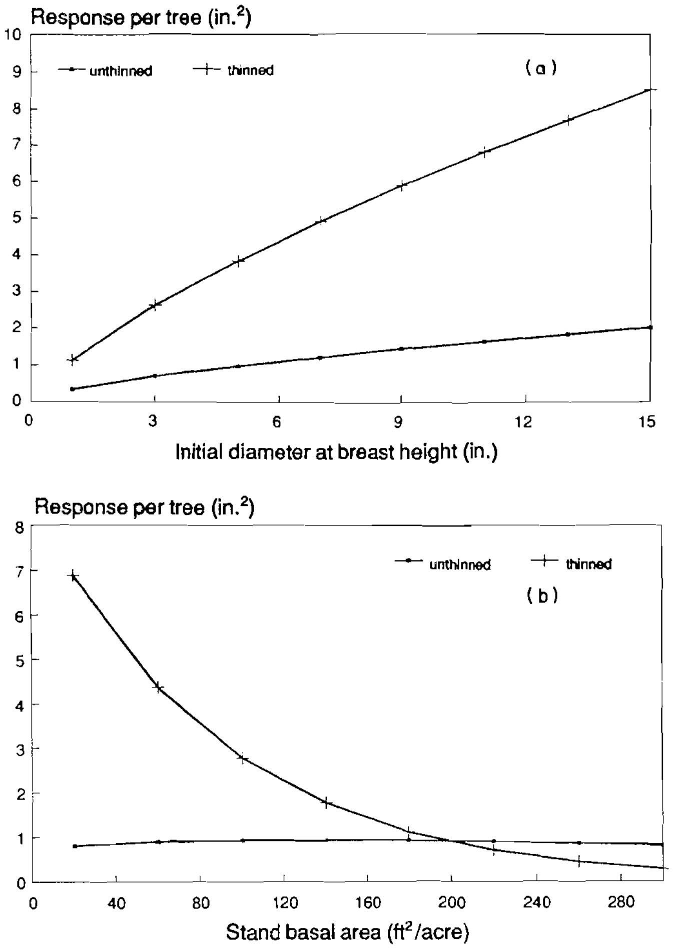

FIG. 3. Predicted 14-year individual-tree basal area response to nitrogen fertilization versus initial diameter at breast height (*a*) and initial basal area per acre (*b*) for grand fir.

$\exp[\widehat{\mathrm{DIS}}_F - \widehat{\mathrm{DIS}}_C]$ for unthinned stands

$\exp[\widehat{\mathrm{DIS}}_{T+F} - \widehat{\mathrm{DIS}}_T]$ for thinned stands

where

$\widehat{\mathrm{DIS}}_F$ = predicted value from eq. 2 with TRT = fertilized only
$\widehat{\mathrm{DIS}}_C$ = predicted value from eq. 2 with TRT = no treatment
$\widehat{\mathrm{DIS}}_{T+F}$ = predicted value from eq. 2 with TRT = thinned and fertilized
$\widehat{\mathrm{DIS}}_T$ = predicted value from eq. 2 with TRT = thinned only

Larger trees in a stand show greater response to fertilization than smaller trees, and this difference in response is somewhat greater in thinned stands (Fig. 3*a*). Thinned stands of lower density produce more individual-tree fertilization response (Fig. 3*b*). The response curve for individual trees in unthinned stands is nearly flat across the range of densities included in this study. These results are consistent with those obtained from a stand-level growth response analysis of the same installations (Shafii *et al.* 1989).

Site quality, no matter how it is expressed in the models, affected overall growth rates and, therefore, the amount of fertilization response. However, as indicated by nonsignificant interactions with treatment, site quality does not affect within-stand distribution of fertilization response. The lat-

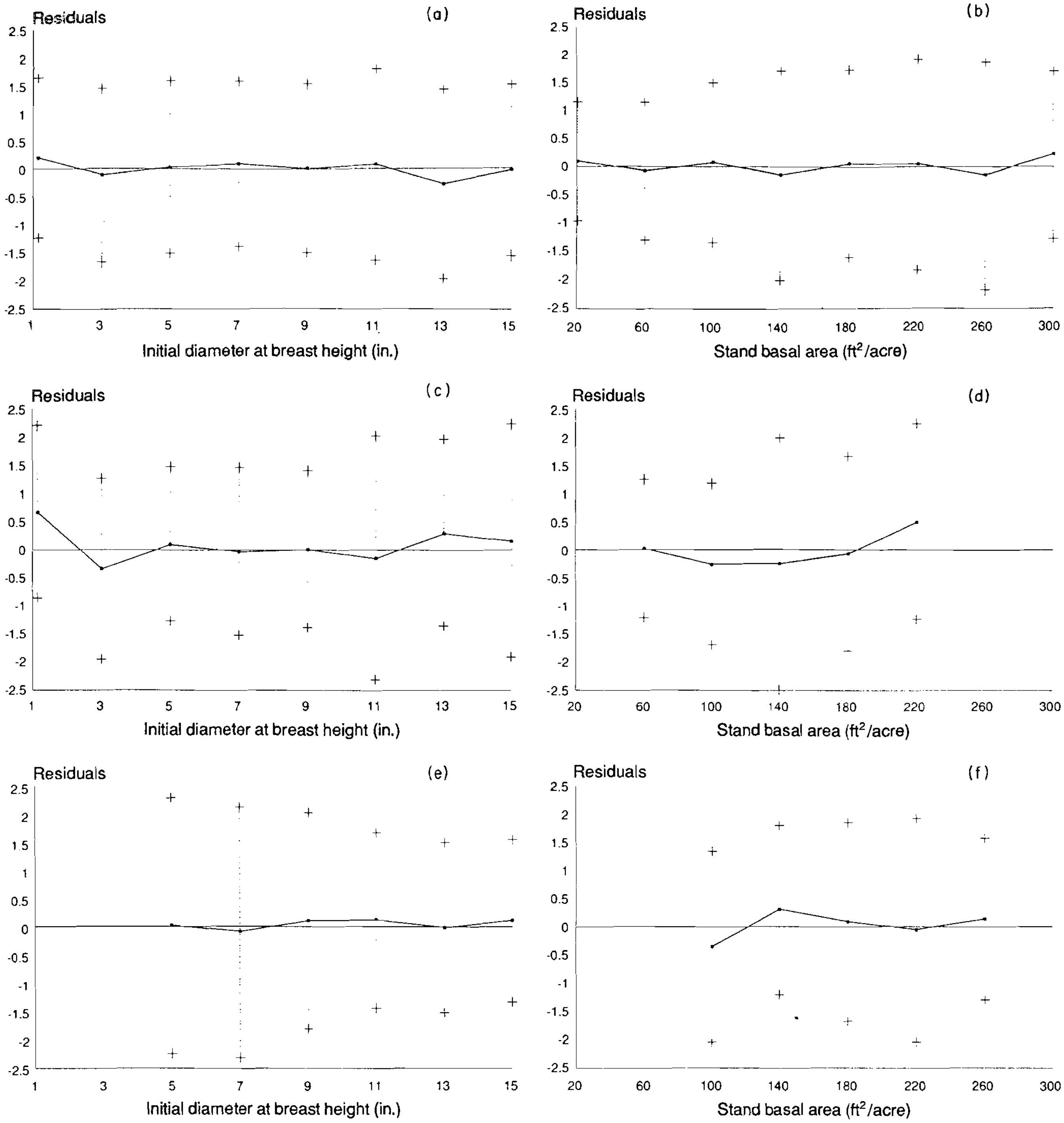

FIG. 4. Individual tree basal area increment model (eq. 2) residuals displayed by initial diameter at breast height and basal area per acre. (*a* and *b*) Development data. (*c* and *d*) ITC test data. (*e* and *f*) Potlatch test data. Plotted values are means ± 2 SD.

ter is affected by stand structural differences, as represented by initial tree size and stand density. The results also indicate that there were no treatment-response differences between grand fir and Douglas-fir.

Regression diagnostics and model validation

Regression diagnostic techniques, described by Belsley *et al.* (1980), were employed to identify the influential subset of data points and also determine sources of collinearity among the explanatory variables. To measure the influence of each observation on model parameter estimates, we computed various influence statistics. Although a small subset of leverage points and potentially influential observations were identified, no action seemed warranted (Shafii 1988). As an overall indication of collinearity, the variance inflation factors associated with parameter estimates were examined, and as a means for diagnosing degrading collinearity, the condition indexes and variance-decomposition proportions were checked. No severe cases of collinearity or ill conditioning were present. In fact, all condition indexes were less than or equal to 16, indicating a relatively weak linear dependency among the regression variates.

Distribution of residuals of the diameter-increment eq. 2 for the 14-year growth period and plotted against dbh and

BA are given in Figs. 4*a* and 4*b*. The plotted values at each setting of the specified explanatory variables are the means ± 2 SD. The residuals do not show any nonlinearities; their variability appears to be approximately constant; and they demonstrate small bias. Residual plots for other explanatory variables not shown here, and those of 5- and 10-year regression equations produced similar results. The average residual was nearly zero for both fertilized and nonfertilized stands.

The two independent data sets, ITC and Potlatch, were used to validate the results of the 10- and 5-year growth models, respectively. In each case, estimated coefficients of the diameter growth model developed from the MS-16 data set (Table 2) were used in an equation to predict the DIS value associated with each tree in the test data set. The residuals defined as the squared difference between observed and predicted values of DIS were then used for model validation. Residual plots similar to those given for the 14-year growth equation were constructed and examined for the test-data sets: ITC (Figs. 4*c* and 4*d*) and Potlatch (Figs. 4*e* and 4*f*). All residuals for both test-data sets, including those of other independent variables not shown here, conformed to the expected pattern and were unbiased. In addition, distribution of residuals by the indicator variable TRT for both test-data sets produced means very close to zero and relatively comparable standard deviation (Shafii 1988). In summary, the individual-tree diameter-increment models produced consistent results over all growth periods, demonstrated favorable statistical properties, and performed well in tests with independent data sets.

Conclusions

The individual-tree growth response analysis clearly showed the impact of nitrogen fertilization in changing the distribution of diameter increments across tree size classes within a stand. This would result in a long-term alteration of stand structure by speeding up the process of crown differentiation.

Larger trees showed more growth response to nitrogen treatments than smaller trees, suggesting that merchantable volume responses and the corresponding economic returns are greater than total volume-response estimates indicate. The greatest fertilization response occurred for trees in thinned stands of low density. Trees growing in stands that were lightly thinned (i.e., those with high basal area after thinning) produced much less individual tree growth than those of low density after thinning. Similar patterns were evident for the fertilization treatment.

Other research indicates that fertilization (*i*) accelerated height, basal area, and volume growth through time (especially for Douglas-fir, grand fir, and western hemlock species (Intermountain Forest Tree Nutrition Cooperative 1987; Regional Forest Nutrition Research Project 1987)), (*ii*) accelerated mortality of smaller trees in a stand, and (*iii*) caused changes in stand development and alteration in the distribution of increments (Bolstad and Allen 1987; Jorgensen and Wells 1987). The results of this study confirm that nitrogen fertilization, particularly in thinned stands, is an effective treatment to increase grand fir and Douglas-fir growth in northern Idaho.

The diameter growth predictive models performed well in tests with independent data sets. The new equations, when incorporated into existing individual-tree growth and yield simulation models, should provide valuable tools for evaluating fertilization treatments, particularly the tradeoffs between individual-tree size and total stand yield.

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