REGIONAL
FOREST
NUTRITION
RESEARCH
PROJECT

VOLUME GROWTH RESPONSE TO FERTILIZATION IN YOUNG DOUGLAS-FIR STANDS

RFNRP Report Number 9

1988

Linda Heath

College of Forest Resources AR-10
University of Washington
Seattle, Washington 98195

The author is a RFNRP Research Assistant. She wishes to thank Mr. Daniel Opalach, Dr. Doug Maguire, and RFNRP Technical Advisory Committee members for helpful comments on the study.

This report is a publication of the Regional Forest Nutrition Research Project, a cooperative program initiated in 1969 to provide forest managers with accurate growth data in managed stands of Douglas-fir and western hemlock in western Oregon and western Washington. Over 30 Pacific Northwest forest industry companies, state and federal agencies, and fertilizer manufacturers provide support and direction for the Project. The RFNRP Report Series is intended to enhance communication of forest fertilization research results within the RFNRP community. Prepared to meet internal RFNRP needs, reports in the series may be descriptions of work in progress as well as final statements of research results.

SUMMARY

Volume growth response to one application of 200 lbs nitrogen per acre in unthinned and thinned Douglas-fir stands of breast height age 25 years or less is estimated for one six-year growth period. Regional mean fertilizer response is 50.3 ± 7.8 ft^3/A/yr in unthinned stands and 44.3 ± 4.5 ft^3/A/yr in thinned stands. These translate into relative growth responses of 16% and 20%, respectively.

Response surface methodology is used to examine trends of volume growth response across basal area and site index. Response trends are similar for unthinned and thinned stands. Response is affected by an interaction of basal area and site index. It is greatest at intermediate basal areas, 50-160 ft^2/A in unthinned stands, and 40-110 ft^2/A in thinned stands. Site index has an increasingly inverse effect as basal area increases. Response varies little over site index in regions of low basal area, decreases moderately as site index increases in the intermediate region, and decreases fairly rapidly in the high basal area region.

Response trends across basal area and Steinbrenner's soil-site index are also examined. The trends are not the same for unthinned and thinned stands, and they do not conform to existing theories of response. Because the RFNRP soil variables were not collected for the purpose of using Steinbrenner's equations to predict soil-site index, a few variables are missing. The predicted soil-site indices tend to be of average value. It is concluded that soil-site index as computed in this paper is not a good substitute for site index.

In the past, response trends have been overlooked because they were not statistically significant in the standard RFNRP statistical analysis. Response surfaces provide for a solid exploration of underlying trends which can then be incorporated into statistical models.

INTRODUCTION

Much of the knowledge of nitrogen (N) fertilizer response in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in the Pacific Northwest pertains to stands thirty years and older. However, interest in the effects of fertilizing younger stands has grown as second-growth stands mature and are replaced. In anticipation of this trend, the Regional Forest Nutrition Research Project (RFNRP) established installations in young stands to study their response to fertilization. The relationship between stand density and fertilizer response is of particular interest (RFNRP 1985).

To perform this analysis, a precise definition of a young stand is needed. A stand may be classified as young based on its stage of development. Miller (1981) defined a young stand as one which has not yet reached the point of maximum current annual increment. A stand could also be considered young if it has not yet reached crown closure, estimated at relative density 0.15 in Douglas-fir (Drew and Flewelling 1979). However, the most direct way to define a young stand is through the choice of an age range. In the present analysis, a young stand is a stand that is less than or equal to 25 years breast height age.

Foresters are interested in how response varies by observable stand attributes, such as basal area, age, or site quality, usually expressed in Douglas-fir as King's (1966) site index. Basal area and age can be measured easily, but in young stands King's site index is not considered reliable. Small errors in height measurement and erratic height growth can greatly affect site index estimates. A better measure of site quality in Douglas-fir may be Steinbrenner's (1979) soil-site index, which is predicted from soil characteristics.

OBJECTIVES

The objectives of this analysis are

1. To present response in gross CVTS* volume periodic annual increment (PAI) to nitrogen (N) fertilizer in natural and precommercially thinned young Douglas-fir stands for one six-year growth period.

2. To investigate response in gross CVTS volume PAI in relation to basal area and site quality in these stands for one six-year growth period.

3. To compare responses across two expressions of site quality, King's site index and Steinbrenner's soil-site index.

METHODS

Data Selection

Data were collected from Douglas-fir installations established in western Washington and western Oregon by the RFNRP. Every installation contains 0.10 acre or larger permanent plots, each receiving fertilizer treatments of either 0, 200, or 400 lbs N/A. Each treatment was applied to at least two plots per installation. Treatments were assigned randomly, and urea fertilizer was broadcast uniformly by hand within plot boundaries and surrounding buffer zones.

Relatively few plots in young stands received the 400 lb N/A treatment. The sample size was deemed inadequate for this analysis, so only data from the 0 and 200 lb N/A treatments were analyzed. Thus, plots receiving 400

---

*Cubic-foot volume, including top and stump, of trees 1.6 inches DBH and larger.

lbs N/A will not be discussed in this report.

Installations are of four main types, referred to as phases. Phase I installations were established in well-stocked stands in 1969-1971. Phase II installations, established in 1971-1973, were thinned to 60% of initial basal area. Phase III installations were established in 1975 to supplement Phases I and II. Some installations were unthinned; other installations contain both unthinned and precommercially thinned (PCT) plots fertilized with either 0 or 200 lbs N/A. A maximum of 400 trees per acre was prescribed for the PCT plots. Phase IV installations, established in 1980 in young stands, were precommercially thinned to 300 trees per acre. The precommercially thinned installations contain six plots, three fertilized with 200 lbs N/A and three controls. For more information on experimental design, see Hazard and Peterson (1984).

The PCT stands of Phases III and IV were combined because the relationship between basal area increment and initial stand conditions does not differ significantly between the two phases (Peterson 1984). The thinning in the young Phase II stands was assumed to be a precommercial thinning similar to those in the young stands of Phase III and Phase IV. Thus, all plots that received any type of thinning were analyzed together. Available treatments, then, are unthinned and fertilized with 0 or 200 lbs N/A (0N, 2N), or precommercially thinned and fertilized with 0 or 200 N/A (0T, 2T).

All plots of initial average breast height age 0-25 years were selected from all phases. The plots contain 80% or greater Douglas-fir by basal area. Average initial plot conditions are summarized by treatment in Table 1.

Field Measurements

Trees

Diameter at breast height (DBH) was measured for all trees greater than 1.55 inches initial DBH and remeasured every other year. Heights were taken using a tape and clinometer to estimate site index and a tarif number for volume calculations for each plot. In Phase I, II, and III installations, heights of ten dominants and codominants were measured; heights of all trees were taken in the young PCT stands of Phase IV. These data were used to compute gross CVTS volume PAI over a six-year growth period.

Soil and other environmental variables

The purpose of soil sampling was to characterize soils before treatment. Standard soil descriptions (Soil Survey Staff 1951) were recorded for a soil pit at each installation located in the buffer zone adjacent to one of the control plots. Samples of the organic layer and mineral soil were collected and analyzed for a number of soil properties (see Ells 1984). Elevation and slope were also recorded for each installation. Elevation was measured with an altimeter or estimated from a topographic map, and slope was estimated with an Abney level.

Soil-Site Index

The soil and other environmental variables were used in Steinbrenner's soil-site equations to predict a soil-site index for each installation. There are four equations: two for regions in western Washington and two for western Oregon. For each equation, Steinbrenner presented a table of coefficients that lists coefficients of the full model and coefficients of all the most explanatory models as the number of predictor variables is reduced by one.

Because Steinbrenner's equations included variables that were not available, it was necessary to choose among the models for each region. Subjective assessments were made to provide the most realistic estimates of site quality. Variables used include effective soil depth, depth of "A" horizon, elevation, and slope.

Growth Response Analysis

Regional mean fertilizer response

Analysis of covariance was used to estimate and test the regional mean fertilizer response. The general model is

$$Y_{ijk} = u + T_i + B_j + \beta(V_{ijk} - V_{...}) \qquad (1)$$

where Y_{ijk} = volume PAI of replicate k, installation j, treatment i
u = mean volume PAI
T_i = main effect of treatment i
B_j = block effect of installation j
β = regression coefficient
V_{ijk} = initial volume
$V_{...}$ = mean volume across all replicates, treatments, and installations

This model is excellent for estimation because it requires few assumptions about the nature of the relationship between the dependent variable and independent variables (see Opalach and Heath 1987). In addition, using installations as blocks is a highly effective device for reducing experimental error.

Effects of basal area and site on response

The emphasis of this study is the trends of response across basal area and site. These trends are captured using response surface methodology. Response surface methodology involves deriving an equation to approximate the response surface, and then producing a visual display of the surface to facilitate analysis.

Although more complex analytical models may be used to create response surfaces, empirical models often mimic growth and response behavior quite well over more limited ranges of the predictor variables. A general second-order polynomial was chosen because most data from biological situations follow a curvilinear relationship (Mead and Pike 1975). Four patterns are produced by the second-order polynomial, 1) a simple maximum or minimum, 2) a stationary or flat ridge, 3) a rising ridge, and 4) a saddle. These are illustrated in Figure 1.

The steps in the analysis are as follows:

1. The equation for estimating untreated growth rate is calculated using control plot data. The form of the equation is

$$CPAI = f(S, BA, S^2, BA^2, S*BA) \qquad (2)$$

where CPAI = volume PAI of control plots, S = King's site index or Steinbrenner's soil-site index, and BA = initial basal area.

2. Equation (2) is used to predict a control growth rate for each fertilized plot. The response (RESPONSE) of the fertilized plot is computed by subtracting the predicted unfertilized growth rate from the observed fertilized growth rate.

3. A prediction equation for response is calculated using the

regression model

$$RESPONSE = f(S, BA, S^2, BA^2, S*BA) \qquad (3)$$

This equation is used to predict response over the region of interest. Responses are mapped on contour diagrams using the Surface II Graphics System (Sampson 1978).

4. The standard error of estimated mean response is calculated using a formula found in most statistics books (for example, Neter and Wasserman 1974; p. 245).

These four steps were executed separately for thinned stands and unthinned stands, once using King's site index as a measure of site productivity, and once representing productivity by Steinbrenner's soil-site index. Thus, four response equations were calculated and analyzed. A residual analysis was performed on all growth and response equations to ensure the models were appropriate.

RESULTS

Site Index Versus Soil-Site Index

The relationship between Steinbrenner's soil-site index (SSI) and King's site index (SI) is illustrated in Figure 2. Points on the lower right-hand-side of the diagonal represent plots whose SSI is lower than its SI. Points on the upper left-hand-side of the diagonal denote plots whose SSI is higher than its SI. The SSI and SI are the same for those points on the diagonal. The horizontal trend among groups of points occurs because all plots within an installation share the same SSI, but each plot possesses its own SI.

The correlation coefficient is .268, indicating a weak positive relationship between the variables. That is, plots of low SI have low SSI and plots of high SI have high SSI. Means of the two variables are similar, but the range and variability of the SSI is less than that of SI.

Regional Fertilizer Response

Mean regional response to 200 lbs N/A in unthinned young stands over a six-year growth period is 50.3 ± 7.8 ft^3/A/yr. Mean response in thinned young stands is 44.3 ± 4.5 ft^3/A/yr. These translate into relative growth increases of 16% and 20%, respectively.

Effects of Basal Area and Site on Response

Response to 200 lbs N/A in young Douglas-fir stands as a function of initial basal area and site is illustrated in Figures 3-6 by contour diagrams. The contour lines represent response in the same way that elevation is portrayed on a topographic map. The interval between contours is 10 ft^3/A/yr. The plus symbols (+) illustrate the basal area-SI range in the underlying data. Each symbol represents the basal area and SI of one plot.

Effects of basal area and SI

The response surface in unthinned stands across basal area and SI is a simple maximum (Figure 3). The contours form diagonal ellipses which indicate response is affected by an interaction of basal area and SI. Generally, as initial basal area increases from almost 0 to 200 ft^2/A, response increases at a decreasing rate, levels off to a maximum, and then decreases. Maximum response of 90 ft^3/A/yr is attained in the basal area range 120-160 ft^2/A and SI 85-105 ft.

As basal area increases, the effect of SI on response increases. Response is fairly constant across SI at low basal areas of approximately 0-50 ft^2/A. At intermediate basal areas, where maximum response occurs, response decreases as SI increases. Changes in response in this intermediate basal area range are gradual, so near-maximum responses can be obtained over a wide range of basal areas and SIs, from 50-160 ft^2/A and SI 85-125 ft. For stands of basal area greater than 150 ft^2/A, response decreases considerably as both basal area and SI increase.

This type of pattern is also exhibited by thinned stands, although basal area ranges from almost 0 to only 125 ft^2/A (Figure 4). As basal area increases, response increases, levels off to a maximum, and then starts to decline. The maximum response of 70 ft^3/A/yr occurs over a wide range, for basal areas of approximately 50-110 ft^2/A and SIs of 85-125 ft. Like the unthinned stands, the effect of SI on response increases as basal area increases. Response decreases as SI increases for stands of basal area higher than 100 to 110 ft^2/A.

An examination of the distribution of underlying raw data points in Figures 3 and 4 reveals that the response surfaces do not include extrapolations into data poor regions. In fact, the surfaces are estimated with data which encompass a wider range than that shown in the figures. Approximately 20% of the data occurs outside the boundaries featured here.

Effects of basal area and SSI

Fertilizer response in unthinned stands plotted across basal area and SSI forms a slowly rising ridge (Figure 5). Interaction between SSI and basal area is again indicated by diagonal contours. Response increases as basal area increases from 0 to 50 ft^2/A, remains fairly constant over 50-150 ft^2/A, then decreases. Response varies little across SSI at low basal area, but response increases as the SSI increases for stands of high initial basal area.

The response surface in thinned Douglas-fir stands mapped over SSI and basal area forms a saddle (Figure 6). The seat of the saddle is quite broad, indicating that response is fairly constant in the SSI range 115-145 ft and the basal area range 20-100 ft^2/A. In the SSI range, response is high at intermediate basal areas for a given SSI, and is less at lower or higher basal areas. Below SSI 115 ft, response increases rapidly as basal area increases. SSI increasingly affects response as basal area increases. For initial basal areas greater than 100 ft^2/A, response decreases as SSI increases across its entire range.

Responses and their standard errors for selected basal areas and SIs or SSIs are presented in Tables 2-5. Estimated mean responses across basal area and SI range from -25.2 to 90.7 ft^3/A/yr in unthinned stands (Table 2), and -0.2 to 79.4 ft^3/A/yr in thinned stands (Table 3). Those responses less than zero can be thought of as being equal to zero because they do not appear to be significantly different from zero. Estimated responses across BA and SSI range from -37.8 to 80.1 ft^3/A/yr in unthinned stands (Table 4), and 16.6 to 126.2 ft^3/A/yr in thinned stands (Table 5).

The data points underlying the models illustrated in Figures 5 and 6 do not cover the extremes of the regions as well as those shown in Figures 3 and 4. The range of SSI is about 105-140 ft. Approximately 10% of the data occurs outside the boundaries.

DISCUSSION

Regional Mean Fertilizer Response

Absolute regional response seems to be greater in unthinned stands, while relative response is greater in thinned stands. This result differs from previous RFNRP analyses (1980) in which both relative and absolute responses of Douglas-fir stands of average age 30 were found to be greater in thinned stands. However, comparisons between the thinned and unthinned young stands should be made cautiously, because unthinned stands are 5 years older on average than the thinned stands.

With the exception of absolute response in the thinned stands, average responses are surprisingly similar to those from the older Phase I (unthinned) and Phase II (thinned) data (RFNRP 1978; RFNRP 1980). The average breast height age of each of these groups of stands is 30 years. The absolute six-year volume growth response in Phase I stands is 53 ± 8 ft^3/A/yr, and 60 ± 8 ft^3/A/yr in Phase II stands. Relative increases were 16% and 22%, respectively. The absolute response in thinned young stands is 16 ft^3/A/yr smaller than response in the Phase II stands, but this is understandable considering the young stands average only 12 years breast height age.

Effects of Basal Area and SI on Response

The trends of response across SI and basal area are similar in both unthinned and thinned stands. Response is highest at intermediate basal areas, and decreases for lower and higher basal areas. In unthinned stands these three basal area regions, low, intermediate, and high, are 0-50, 50-

160, and 160-200 ft^2/A, respectively. In thinned stands, the regions are approximately 0-40, 40-110, and 110-125 ft^2/A. A similar pattern of response has also been observed in older unthinned Douglas-fir stands (Strand and DeBell 1979).

In the region of low basal area, response appears to be limited mainly by initial stocking. Response varies little over site index in this region. In the intermediate basal area region, stocking levels are high enough to produce good growth, but low enough so that growth response is not limited by lack of space. Response is moderately inversely affected by site index in this region, indicating growth is limited by a lack of nitrogen on lower sites. In regions of high basal area, growth response decreases considerably as SI increases. It appears that growth in highly stocked, low site stands is affected more by lack of nitrogen than lack of space or other competition effects, but at higher SI the other effects become more important.

The decrease in response at high basal areas is less in the thinned stands than in unthinned stands, partly because the maximum basal area in is only 125 ft^2/A in thinned stands and 200 ft^2/A in unthinned stands. In addition, this decrease in response in thinned stands could be an artifact of using a second degree polynomial or it could be a thinning treatment effect. Most of the thinned stands of higher basal area had 40% of their original basal area removed, while stands of lower basal area were precommercially thinned.

Although the investigation of trends of response is the main purpose of this analysis, the statistical significance of responses at various basal areas and site indices can be calculated from Table 2-3. Many of the responses are significantly different from zero. The other notable feature of these tables is that the estimates of response are high compared to the regional mean fertilizer response. For example, the regional mean fertilizer response in unthinned stands is 50.3 ft^3/A/yr, but response at the mean site index and mean basal area of unthinned stands is closer to 70 ft^3/A/yr according to Table 2. This occurs because the mean values of BA^2, S^2, and BA*S which produce the regional mean fertilizer response in the RFNRP data are not equal to the values used in the creation of the tables. When making point predictions for a given basal area and site index, basal area squared and site index squared are calculated by simply squaring basal area and site index. However, means of the variables are used in the calculation of the regional mean fertilizer response, and the mean of the squared variable is rarely equal to the mean of that variable, squared.

Effects of Basal Area and SSI on Response

The relationship between SSI and response is not clear. Response trends based on SSI differ considerably from those based on SI. In addition, the response trends based on SSI for unthinned and thinned stands differ from each other.

The main problem with SSI is that it is an installation level variable. The variability in the soils may be such that soils variables should be determined for each plot Also, an installation level independent variable may cause statistical problems because response, basal area, and SI are plot level variables.

Another problem with SSI is that its range is narrower than that of site index. The range was kept the same as that of SI only for ease of comparison. Response predictions outside the SSI range 105-140 ft are based on limited data. This is reflected in the higher standard errors for responses in SSI 85 and 145 columns in Tables 4 and 5 as compared with the corresponding standard errors for SI (Tables 2 and 3).

A final concern is that the correlation between SI and SSI is low. Although problems do exist with SI in young stands, it still appears to be a more consistent measure of site productivity than SSI as calculated here. Ridge systems such as the one in Figure 5 often mean that the variables under study are not the variables driving the system (Box and Draper 1987). The actual variables may be difficult or costly to measure, so more convenient variables are used which do not well represent the true hard-to-measure factors. If SI is viewed as an unacceptable measure of site productivity in young RFNRP stands, perhaps available soil variables should be integrated into an alternative index of productivity.

CONCLUSIONS

Thinned and unthinned young Douglas-fir stands respond to one application of 200 lbs N/A over a six-year period. Volume growth response is similar to that previously reported for older stands. Absolute volume growth is slightly less in thinned stands, but the average breast height age of these stands is five years less than that of the young unthinned stands.

Trends of volume growth response across basal area and King's site index are similar for thinned and unthinned stands. Response is affected by the interaction of these two variables. In regions of low basal area, response increases with increasing basal area and does not vary substantially across SI. In the intermediate basal area region, near-maximum response can be obtained over a wide range of basal area and SI. Response decreases gradually as SI increases. At high basal areas, response decreases fairly rapidly as basal area and SI increases.

Results pertaining to the SSI are not consistent, nor do they exhibit expected behavior. Some of the soil variables needed for Steinbrenner's equations were not available, and the absence of these variables probably affects the results. If King's site index is not acceptable as a measure of site productivity in young stands, actual soil variables may be a better alternative. As computed in this study, SSI is not a good substitute for SI.

Response surface methods and the accompanying contour diagrams have proven to be useful for preliminary analysis of the young stand data, and should serve as an important guide for future analyses. In the past, trends may have been overlooked because they were not statistically significant. This approach can be used to identify those trends by allowing for visualization of response over stand variables such as basal area and site index concurrently.

LITERATURE CITED

Box, G. E. P., and N. Draper. 1987. Empirical model-building and response surfaces. John Wiley and Sons, Inc., New York. 669 p.

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

Drew, T. J., and J. W. Flewelling. 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. For Sci 25:518-532.

Ells, R. 1984. The Regional Forest Nutrition Research Project information management system. Unpublished, RFNRP Report No. 3. 45 p.

Hazard, J. W., and C. E. Peterson. 1984. Objectives and analytical methods of the Regional Forest Nutrition Research Project. Inst of Forest Resources Contrib 53, Univ Washington, Seattle, WA. 23 p.

King, J. E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser For Pap No 8, Weyerhaeuser Company For Res Center, Centralia, WA. 49 p.

Mead, R., and Pike, D. J. 1975. A review of response surface methodology from a biometric viewpoint. Biometrics 31:803-851.

Miller, H. G. 1981. Forest fertilization: some guiding concepts. Forestry 54: 157-167.

Neter, J., and W. Wasserman. 1974. Applied linear statistical models. Richard D. Irwin, Inc., Homewood, IL. 842 p.

Opalach, D., and L. Heath. In Press. Evaluation of long-term fertilizer response. Proceedings of IUFRO Forest Growth Modelling and Prediction Conference, August 24-27, 1987, Minneapolis, MN.

Peterson, C. E. 1984. Fertilization of Douglas-fir plantations in the Pacific Northwest RFNRP Cooperative. P. 637-645 In Proc IUFRO Sympos on Site and Productivity of Fast Growing Plantations. D. C. Grey et al., (eds). April 30-May 11, Pretoria and Pietermaritzburg, South Africa.

Regional Forest Nutrition Research Project. 1978. Biennial report 1976-1978. Inst Forest Resources Contrib 37, Univ Wash, Seattle. 46 p.

Regional Forest Nutrition Research Project. 1980. Biennial report 1978-1980. Inst Forest Resources Contrib 39, Univ Wash, Seattle. 44 p.

Regional Forest Nutrition Research Project. 1985. Proposal for five-year extension of research. Unpublished, College of Forest Resources, Univ Wash, Seattle. 34 p.

Sampson, R. J. 1978. Surface II Graphics System. (Revision One). Number 1 in a Series on Spatial Analysis. Kansas Geological Survey, Lawrence, KS. 240 p.

Soil Survey Staff. 1951. Soil survey manual. USDA Handbook No. 18, US Government Printing Office, Washington, D. C.

Strand, R. F., and D. S. DeBell. 1979. Growth response to fertilization in relation to stocking levels of Douglas-fir. P. 102-106 In Proc Forest Fertilization Conf. S. P. Gessel, R. M. Kenady, and W. A. Atkinson, (eds). Inst of Forest Resources Contrib 40, Univ Washington, Seattle. 275 p.

Steinbrenner, E. C. 1979. Forest soil productivity relationships. P. 199-229 In Forest Soils of the Douglas-fir Region. P. E. Heilman, H. W. Anderson, and D. M. Baumgartner, (eds). Washington State University Cooperative Ext Serv, Pullman, WA. 298 p.

Table 1. Average stand conditions for each treatment at the beginning of the growth period.

Stand Attribute	0N	2N	0T	2T
Site index	122	124	126	127
Soil-site index	119	120	118	119
Age	17	17	12	12
Trees/A	964	1022	376	379
Basal Area	124	124	50	49
Volume	2694	2632	892	877
BA PAI	8.7	10.7	8.5	10.6
Volume PAI	320	371	227	272
Relative Density	54	55	21	21
Quad. mean DBH	5.0	4.9	4.8	4.8
Sample size	68	67	81	83

where units of measurement are

Site index	- feet, base age = 50 years (King 1966)
Soil-site index	- feet, base age = 50 years (Steinbrenner 1979)
Age	- years, measured at breast height
Basal area	- ft^2/A
Volume	- ft^3/A, CVTS
BA PAI	- $ft^2/A/yr$
Volume PAI	- $ft^3/A/yr$
Relative Density	- Curtis (1982)
Quad. mean DBH	- inches

Table 2. Estimated response ($ft^3/A/yr$) in gross CVTS volume PAI (and standard error) of unthinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and site index. The growth period is the six years following fertilization.

Basal area (sq ft/A)	Site index (feet) 85	105	125	145
40	37.1 (36.1)	53.4 (20.6)	54.3 (15.6)	39.8 (16.9)
80	72.4 (27.4)	80.6 (14.2)	73.1 (12.8)	50.3 (16.6)
120	89.9 (26.9)	89.7 (13.6)	74.1 (12.0)	43.0 (18.8)
160	90.7 (27.3)	81.1 (16.3)	57.2 (10.0)	17.9 (21.3)
200	71.3 (44.4)	54.6 (24.3)	22.4 (14.3)	-25.2 (28.1)

Table 3. Estimated response ($ft^3/A/yr$) in gross CVTS volume PAI (and standard error) of thinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and site index. The growth period is the six years following fertilization.

Basal area (sq ft/A)	Site index (feet) 85	105	125	145
20	21.0 (26.8)	45.6 (13.0)	48.8 (7.7)	30.6 (7.4)
40	44.7 (17.7)	64.4 (7.7)	62.7 (6.7)	39.5 (6.9)
60	60.9 (14.9)	75.7 (8.5)	69.0 (8.0)	41.0 (9.2)
80	69.5 (18.9)	79.4 (12.1)	67.8 (8.7)	34.8 (12.2)
100	70.6 (25.9)	75.5 (16.0)	59.0 (9.0)	21.2 (16.2)
120	64.1 (34.1)	64.0 (20.5)	42.6 (10.7)	-0.2 (21.9)

Table 4. Estimated response ($ft^3/A/yr$) in gross CVTS volume PAI (and standard error) of unthinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and soil-site index. The growth period is the six years following fertilization.

Basal area (sq ft/A)	Soil-site index (feet) 85	105	125	145
40	44.6 (37.5)	48.3 (18.4)	43.6 (15.6)	30.6 (39.4)
80	46.7 (35.5)	60.3 (15.7)	65.5 (12.7)	62.3 (27.0)
120	33.7 (40.5)	57.1 (15.2)	72.1 (12.9)	78.8 (21.2)
160	5.5 (37.5)	38.8 (16.9)	63.6 (11.7)	80.1 (22.2)
200	-37.8 (68.5)	5.2 (26.4)	39.9 (15.8)	66.2 (30.3)

Table 5. Estimated response ($ft^3/A/yr$) in gross CVTS volume PAI (and standard error) of thinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and soil-site index. The growth period is the six years following fertilization.

Basal area (sq ft/A)	Soil-site index (feet) 85	105	125	145
20	64.9 (33.7)	41.5 (10.8)	39.8 (8.3)	59.8 (25.6)
40	85.3 (33.2)	54.9 (8.7)	46.2 (7.4)	59.2 (22.5)
60	101.6 (34.3)	64.2 (9.2)	48.6 (9.0)	54.7 (21.4)
80	113.9 (37.2)	69.5 (10.9)	46.9 (10.1)	46.0 (20.8)
100	122.1 (42.1)	70.8 (14.7)	41.2 (11.0)	33.3 (20.2)
120	126.2 (49.6)	67.9 (21.5)	31.4 (14.2)	16.6 (20.4)

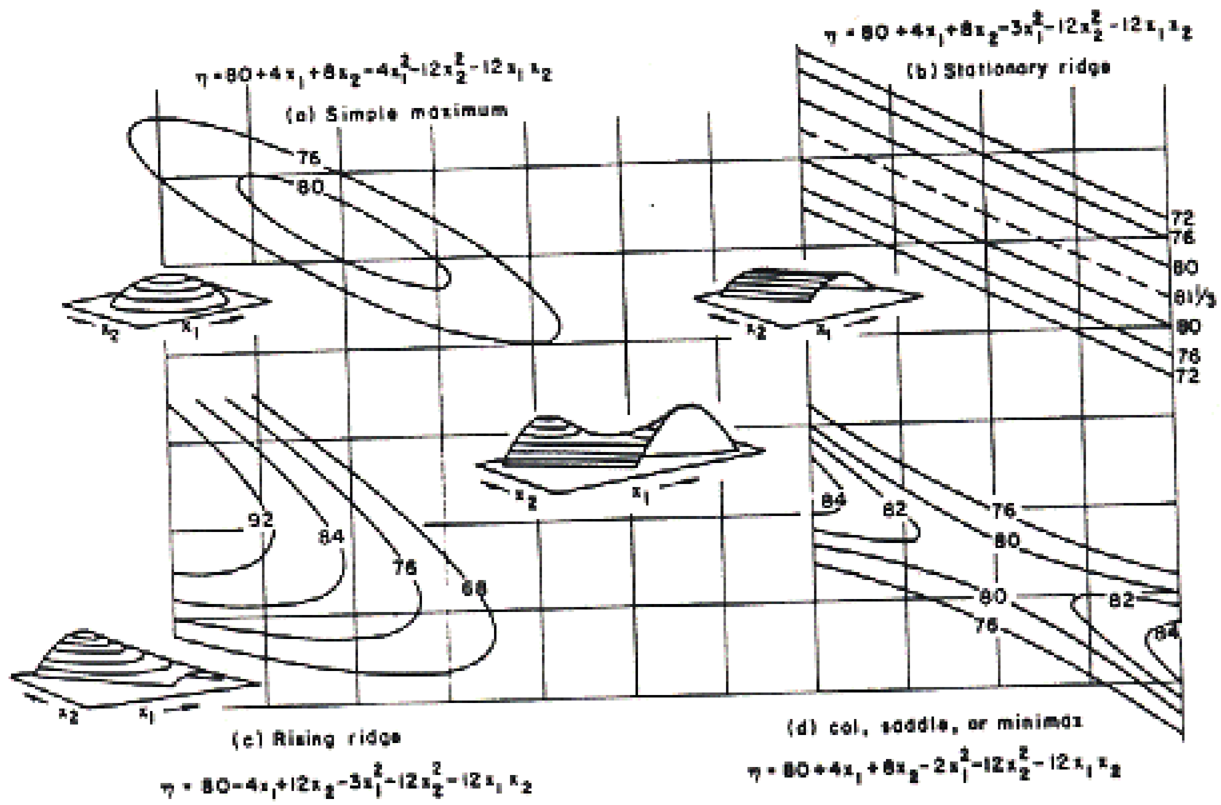

Figure 1. Examples of types of surfaces produced by second-order polynomials with two predictor variables, x_1 and x_2.
Source: Box and Draper 1987, Figure 2.2

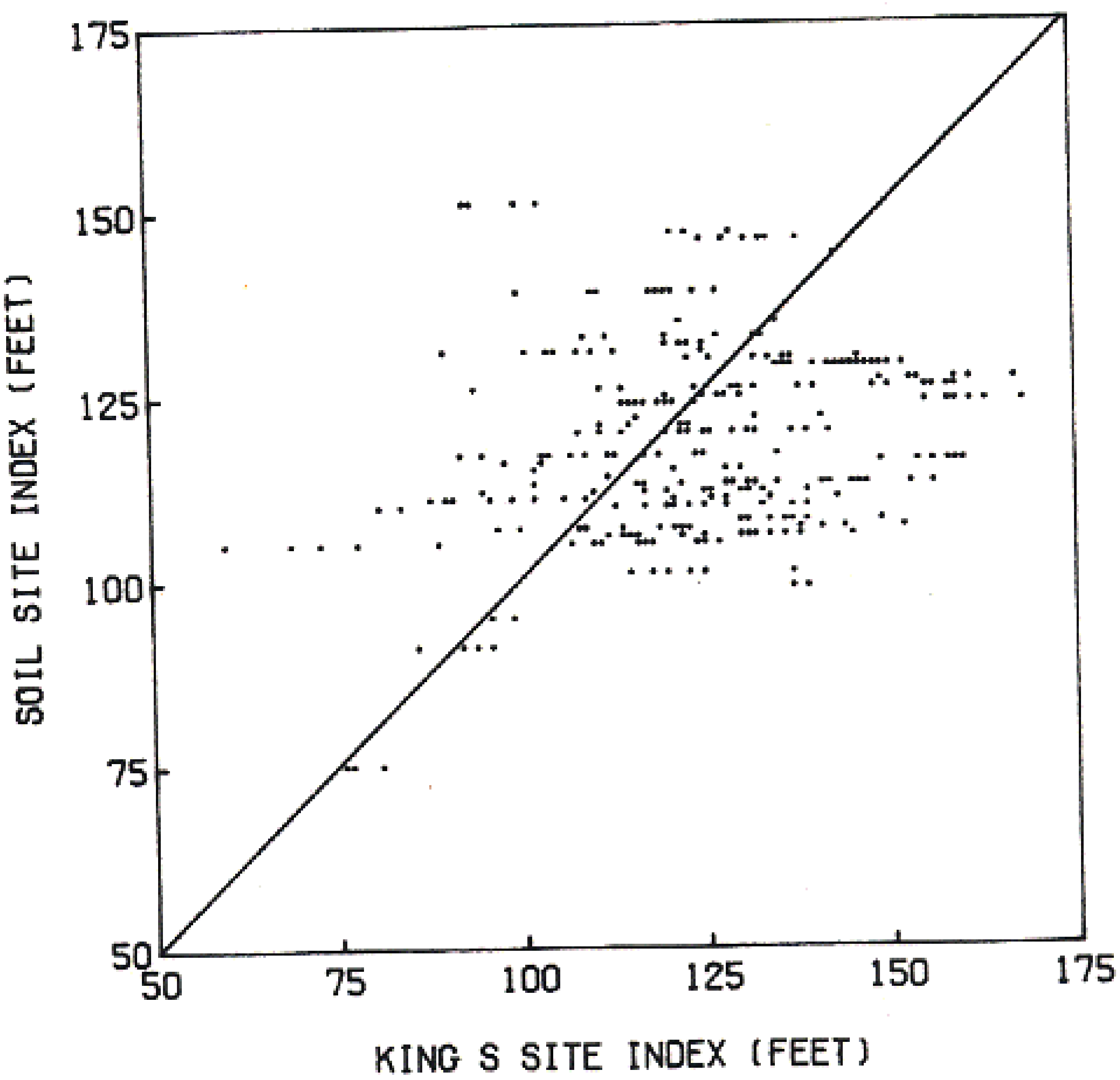

Figure 2. Soil-site index versus site index for RFNRP installations in young Douglas-fir stands.

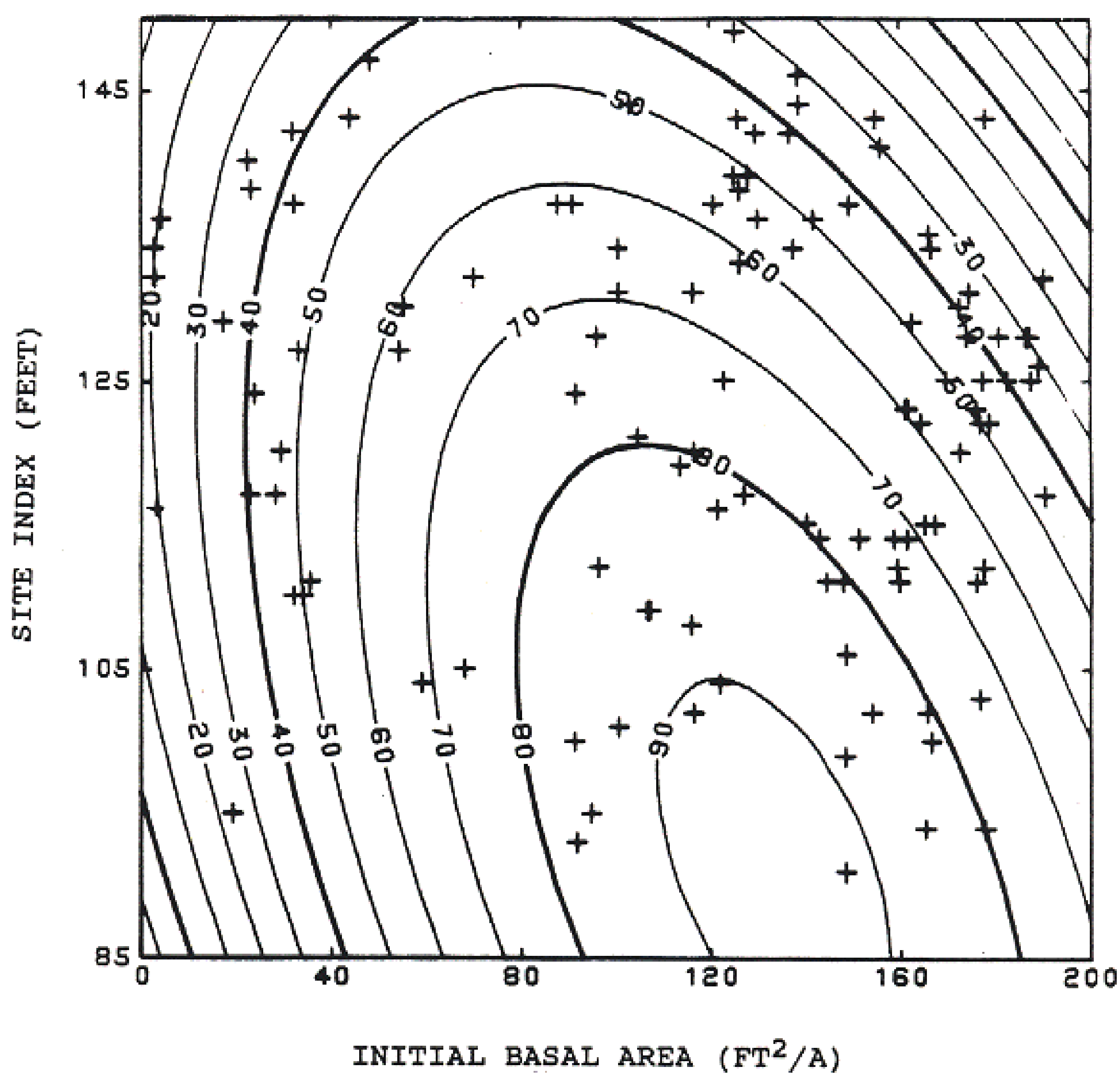

Figure 3. A contour diagram of estimated response (ft^3/A/yr) in gross CVTS volume PAI over a six-year period in unthinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and site index. The plus symbol (+) represents a data point (not a response value) in the basal area-site index plane.

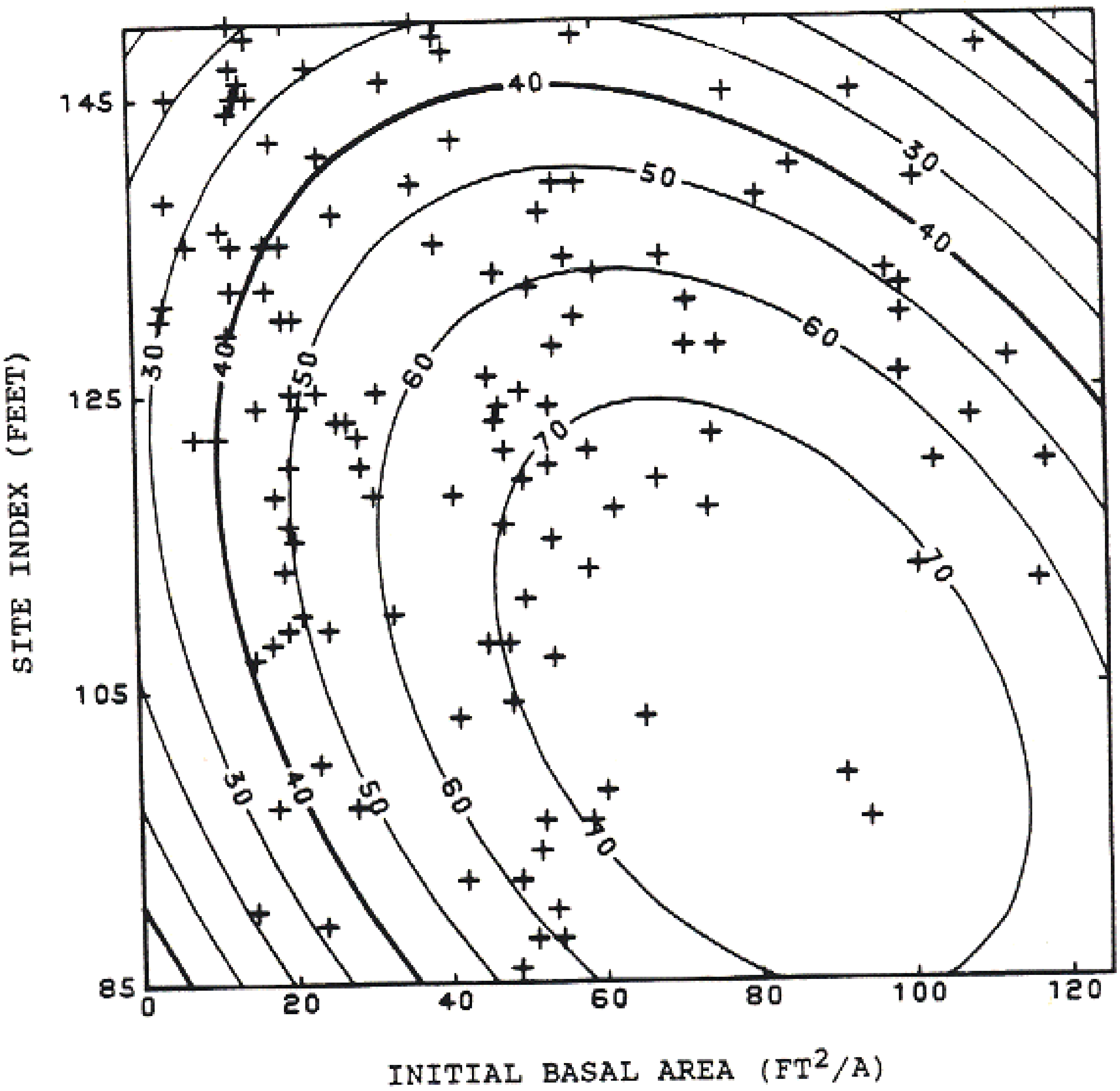

Figure 4. A contour diagram of estimated response (ft^3/A/yr) in gross CVTS volume PAI over a six-year period in thinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and site index. The plus symbol (+) represents a data point (not a response value) in the basal area-site index plane.

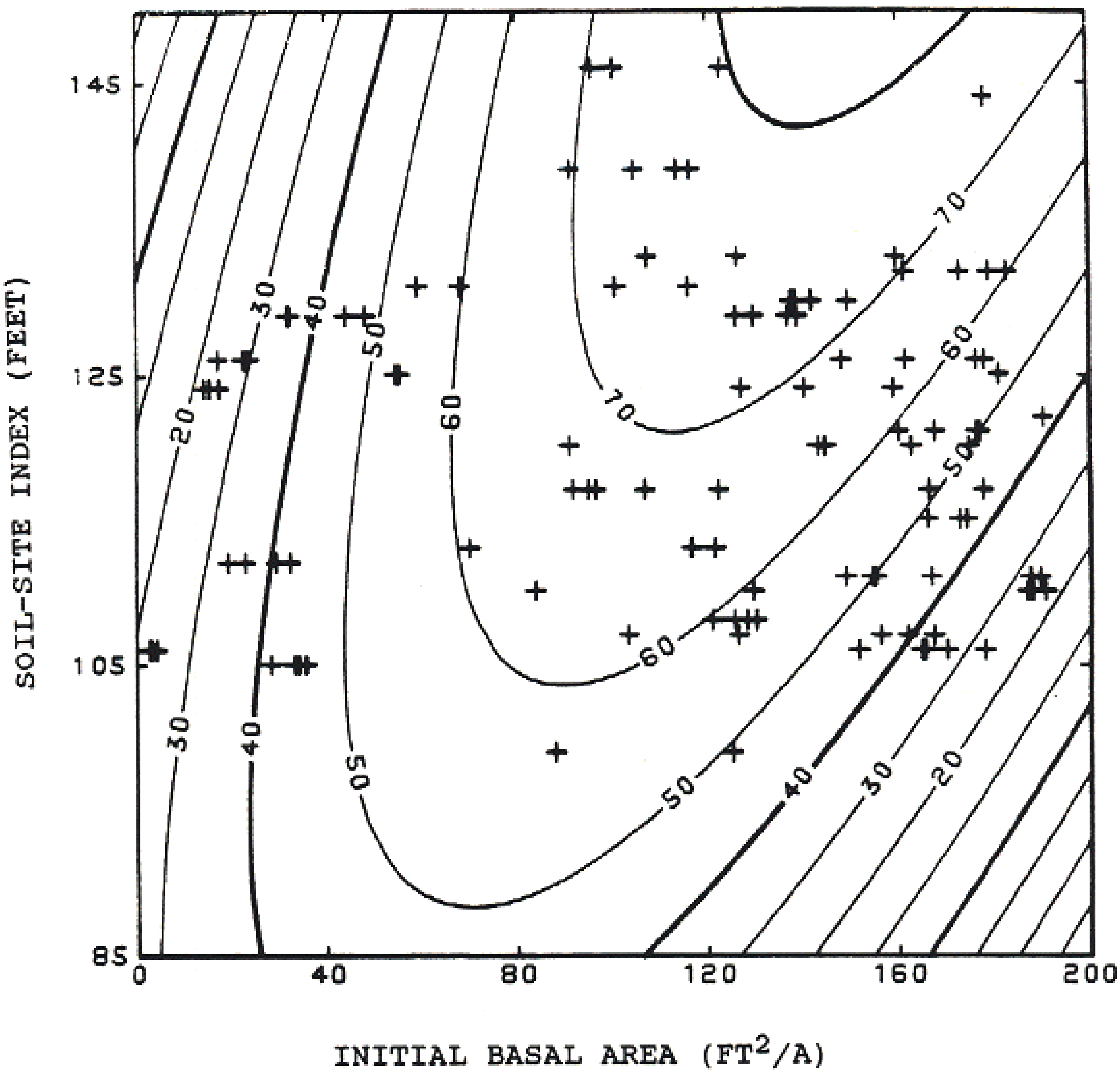

Figure 5. A contour diagram of estimated response (ft^3/A/yr) in gross CVTS volume PAI over a six-year period in unthinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and soil-site index. The plus symbol (+) represents a data point (not a response value) in the basal area-soil-site index plane.

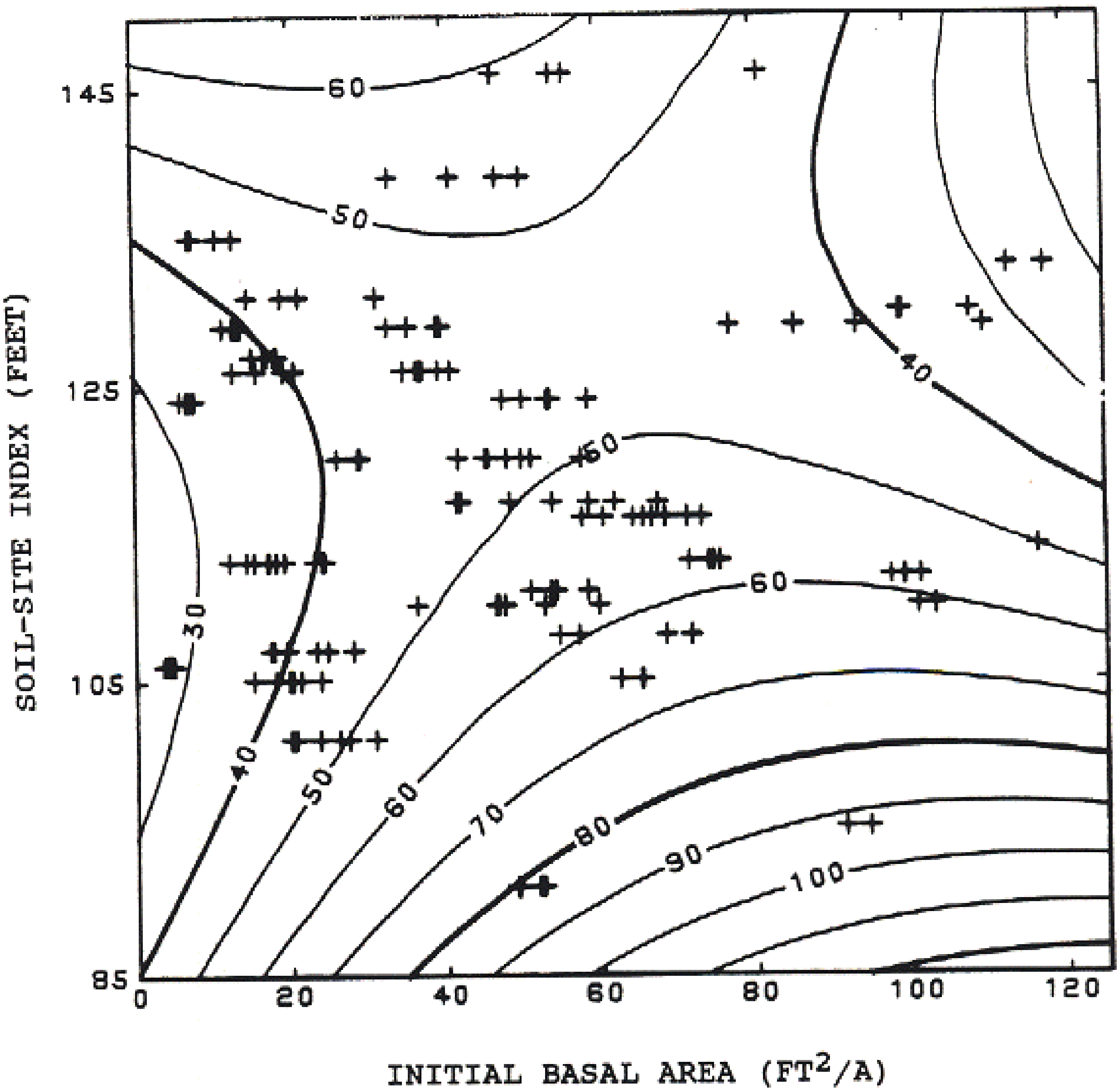

Figure 6. A contour diagram of estimated response (ft^3/A/yr) in gross CVTS volume PAI over a six-year period in thinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and soil-site index. The plus symbol (+) represents a data point (not a response value) in the basal area-soil-site index plane.