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Part III

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Predicting Six-year Douglas-fir Response to Nitrogen Fertilization Using Outputs from Process Models

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PROCESS MODEL OUTPUTS AS PREDICTORS OF SIX-YEAR DOUGLAS-FIR RESPONSE TO NITROGEN TREATMENT

The modeling efforts detailed in part II of this annual report indicated that we do have some ability to predict Douglas-fir response to N fertilization. However, our ability to interpret the results is often limited, in large part due to the sorts of variables used as predictors.

Consider site elevation as such a variable. This is a feature of the site that can be easily measured and has been shown to correlate with tree growth. But what is the meaning of such a correlation? Does a change in elevation imply a difference in temperature and/or moisture regimes? Are the trees growing at different elevations also different genetically? How do elevation differences translate into differences in transpiration, photosynthesis, and carbon fixation? How can we hope to sort out these various factors?

We could avoid these problems in interpretation if we could measure the biological processes taking place and the environmental conditions that directly controlled those processes. Unfortunately, we have neither the time nor material resources to do that. But, by incorporating known theoretical biological and physical relationships, process simulation models offer us a way to predict many of these environmental conditions and growth process outcomes from information we already have available or can collect from other sources. Our efforts to date have focused on the following areas:

1) the genetic diversity of Douglas-fir across the various locations,

2) the soil moisture budget for each installation under average conditions, and

3) the differences in biological processes (i.e. transpiration, photosynthesis, and respiration rates) among the installations under average conditions.

Much possible future work exists in this area. For example, we could attempt to predict environmental and biological changes within the actual measurement period, using local climatic records. Such information might enable us to explain some of the seeming anomalies in our response data.

Methods

Indexing Douglas-fir genetic diversity

Based on common garden behavior of seedlings grown from different seed sources, Rehfeldt (1989, 1991) has developed indices that account for much of the variation in Douglas-fir genetic potential in the intermountain region. These indices make use of location (latitude and longitude) and elevation of the seed source to predict the relative ability of seedlings grown from that seed to grow in height and tolerate freezing in fall, winter, and spring.

We have made use of Rehfeldt's equations to calculate a height growth and freezing tolerance potential for most of the installations in the Douglas-fir experiment. The genetics work did not cover sites in central Washington, and the distance from the sampled area was too great to allow extrapolation; thus, no indices were calculated for our central Washington installations. Although northeast Oregon was also not covered in the genetics study, we felt that the close proximity to sites studied in southwest Idaho would permit us to extrapolate the genetics results to our Oregon installations; however, this assumption needs careful examination before we draw strong conclusions about the genetic control of fertilization response for our Oregon sites.

The two indices show a strong negative correlation with one another ($\rho=-0.9202$ for our data): height growth potential is highest at low elevations while freezing tolerance potential is greatest at high elevations. The variation in these indices across the installations in the Douglas-fir fertilization experiment is shown in Table 1. For our sites, height growth potential is highest in NE Washington and northern Idaho and decreases as one moves south and east; freezing tolerance potential shows the opposite trend. The influence of elevation and location on these indices are confounded in our data set, as elevation shows a significant negative correlation with both latitude (p=-0.6394) and longitude (p=-0.4348).

Table 1. Variation in indices of Douglas-fir genetic potential across five regions of the IFTNC Douglas-fir fertilization experiment. Values presented are the mean, minimum, and maximum for both height growth potential and freezing tolerance potential for each region.

Region:	Height Growth			Freezing Tolerance		
	Mean	Min	Max	Mean	Min	Max
North Idaho	3.08	2.11	3.78	-176	-314	2
Montana	1.46	0.61	2.32	51	-114	178
Central Idaho	0.65	0.19	1.29	235	97	301
NE Oregon	1.76	0.15	3.28	19	-244	322
NE Washington	3.28	2.71	4.26	-64	-249	23
Overall	2.17	0.15	4.26	-2	-314	322

Extrapolation of installation-specific climatic data

In order to calculate soil moisture and carbon fixation budgets for our various installations, we first needed to gather site-specific climatic data for all of the sites. Since no climate records were available for the actual sites, we needed to extrapolate data from long-term weather stations to our installation locations. To accomplish this, we used a microclimate simulation model, MTCLIM, developed for just such a purpose (Running et al 1987, Hungerford et al 1989). Using information on elevation, slope, aspect, east and west horizon, and mean annual precipitation, the model extrapolates daily temperature and precipitation data from a base station to the remote site. In addition, the model predicts daily radiation inputs and relative humidity for the site.

Information on elevation, aspect, slope, and horizons had been collected at each of our sites, but no measure of annual precipitation was available. Instead, we had to predict mean annual precipitation using regression models developed from local long-term precipitation data. The data base consisted of 30 year (1961 - 1990) average annual precipitation figures for National Weather Service stations and high elevation Sno-tel stations maintained by the Soil Conservation Service. After data editing, we had information on 69 stations covering the area where our north and central Idaho Douglas-fir installations are located. Although more complicated models were tried, a simple linear regression of mean annual precipitation on elevation gave good results (R^2 = 0.87, CV = 16%); the slope varied significantly (p = 0.0001) with region. The model is given below:

$$\text{MAP} = 2.14 + 0.011877 * \text{Elevation (for north Idaho)}$$

$$= 0.68 + 0.006520 * \text{Elevation (for central Idaho)}$$

where MAP = mean annual precipitation (in/yr) and elevation is in feet. This model has been used to predict mean annual precipitation for our 19 installations in northern Idaho and 14 installations in central Idaho.

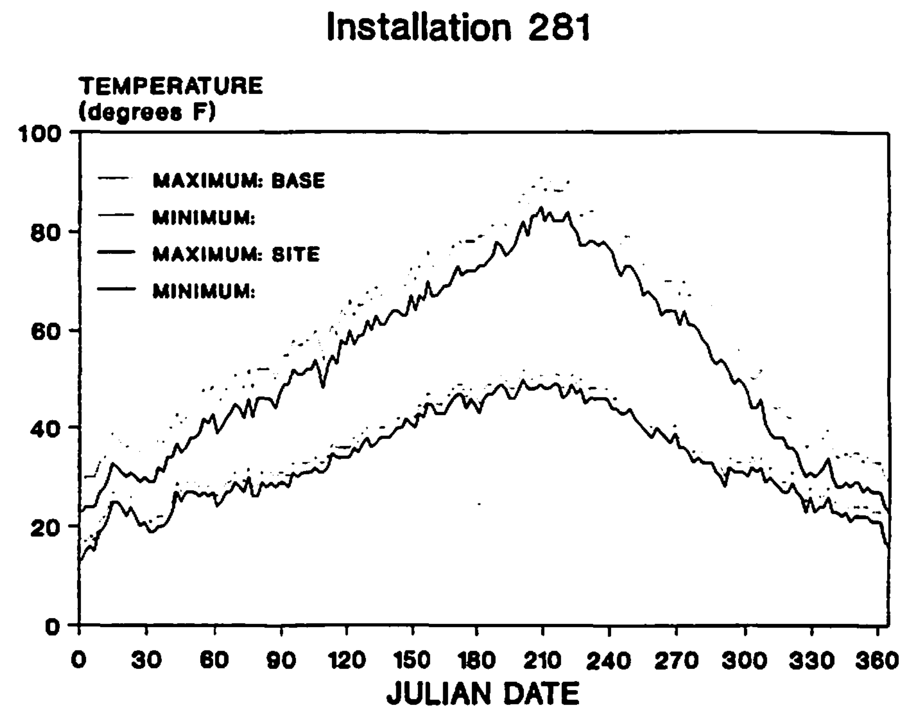
We obtained the Idaho weather data through the Northwest Hydrologic Information Management System (Bluske et al 1987) maintained at the University of Idaho. This system also contains daily records for many of the NWS stations in Washington, but does not cover Oregon or Montana. We are currently gathering daily data for a number of stations in the later two states and are assembling Sno-tel data for Washington, Montana, and Oregon. Completion of this data gathering will allow us to predict daily climate for all of our Douglas-fir installations.

In addition to confining our current climate modeling efforts to Idaho sites, we have limited ourselves to considering an average composite year. This was constructed by averaging daily precipitation and minimum and maximum temperature values over the period from 1965 through 1988 for all the NWS base stations we used for extrapolation. This "average" year was used to drive the MTCLIM model, producing an average climatic pattern for each of the Idaho installations.

An example of the MTCLIM extrapolation results for installation 281, a site east of St. Maries in northern Idaho, are shown in Figure 1. The installation is located on a northeast facing slope at 3200 feet, while the base station is located at the St. Maries Ranger Station at 2220 feet. The upper panel shows how base station minimum and maximum daily temperatures (the dotted lines) were extrapolated to temperatures for the installation (the solid lines), while the lower panel shows similar results for daily precipitation. Because the base station data are averages of 24 years, both the temperature and precipitation figures are smoother than an actual year's data would be. Temperatures are lower at the site than at the base station primarily due to the difference in elevation; different lapse rates are applied to maximum and minimum temperatures. Daily precipitation values are adjusted from the base station to the site proportional to the ratio of respective mean annual precipitation values. Calculation details are available in the paper by Hungerford et al (1989).

Predicting the pattern of soil moisture status

Daily temperature and precipitation values for the Idaho installations were translated into site moisture deficit and soil moisture availability using a water balance program coded at the University of Idaho. The program is based on concepts put forth by Zahner (1966) and Zahner and Stage (1966). Daily temperatures are transformed into potential evapotranspiration; the difference between this and daily precipitation is soil moisture demand. If the soil is not able to completely fulfill the demand, a deficit is created. Withdrawal of soil moisture is dependent



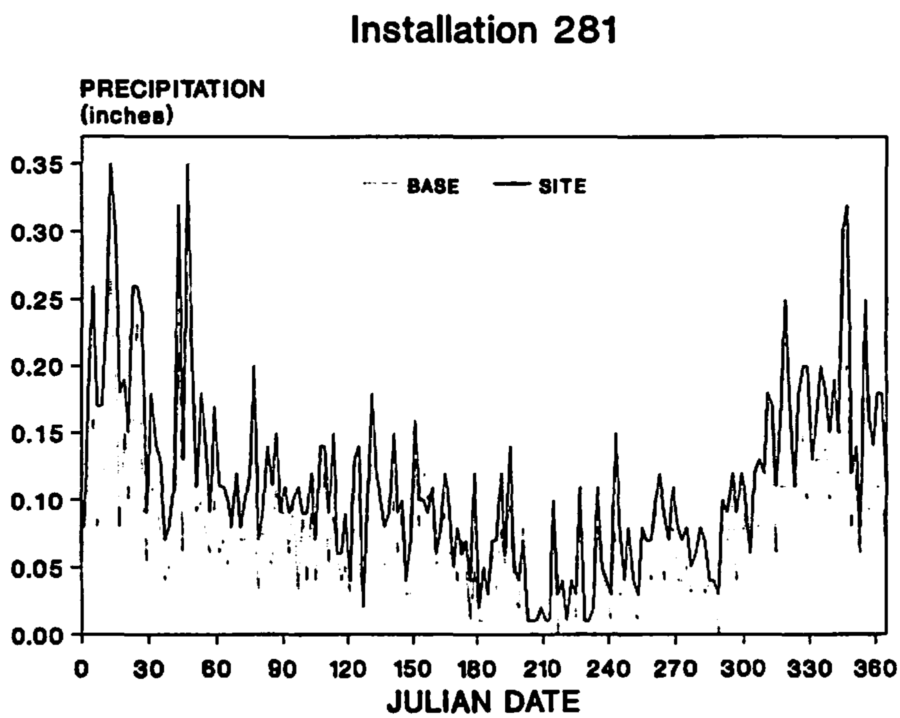


Figure 1. The relationship between daily base station and on-site weather for Douglas-fir installation 281. The upper panel is temperature while the lower is precipitation.

on current available moisture, total moisture holding capacity, and soil texture. Thus, in addition to daily temperature and precipitation values, the program requires information on soil moisture holding capacity, soil texture, and the actual available soil moisture on a given date. Program code and documentation is available from the IFTNC.

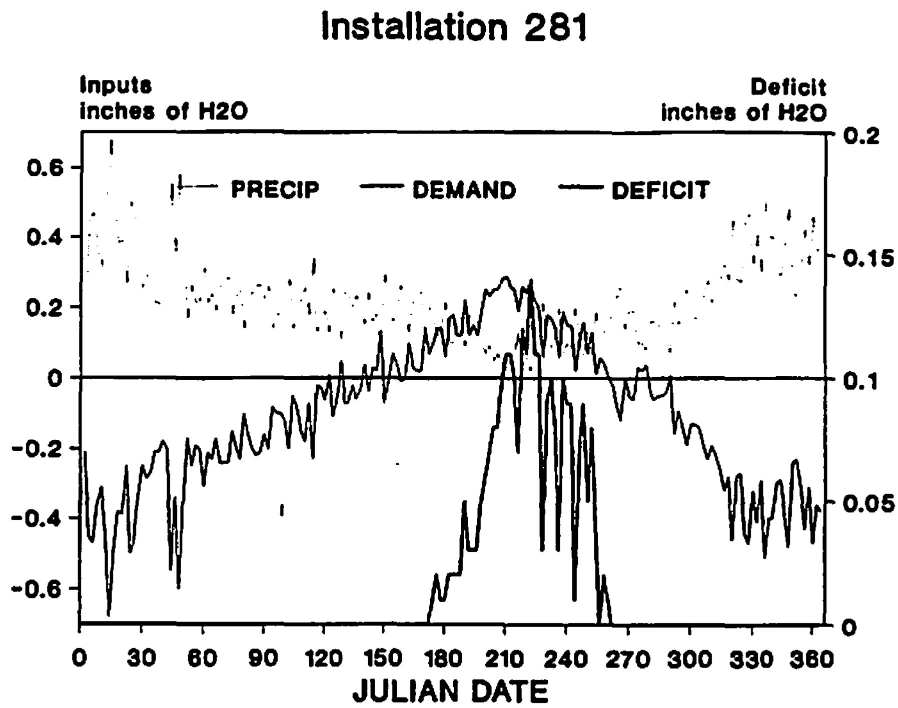
Figure 2 shows the soil moisture conditions calculated for installation 281 using the "average" climatic conditions discussed above. The soil was assumed to be saturated on January 1. The upper panel shows that precipitation is able to fulfill evapotranspiration loss until May; at that point positive soil moisture demand starts to occur. However, the soil is able to meet all demands until late June; then moisture deficits begin to occur and continue through mid-September. In October, a combination of decreased evapotranspiration and increased precipitation have driven demand back to zero, so that no further deficit occurs.

The lower panel in Figure 2 shows the cumulative effects of the processes discussed above on total deficit (a measure of the site's inability to support maximum growth due to lack of moisture) and soil available moisture. Soil moisture starts to decline in late May, reaches a low of about 39% of capacity in mid-September and returns to full capacity in late November. A total deficit of 2.66 inches of water was calculated for the site.

From this information we have derived a number of variables reflecting the "average" moisture conditions of the site. These variables include the total water holding capacity, the total water deficit, the length of the period during which water deficit occurs, the minimum available soil moisture, and the date when this minimum occurs.

Predicting rates of transpiration, photosynthesis and productivity

Biological measures of "average" tree activity were predicted for the Idaho installations



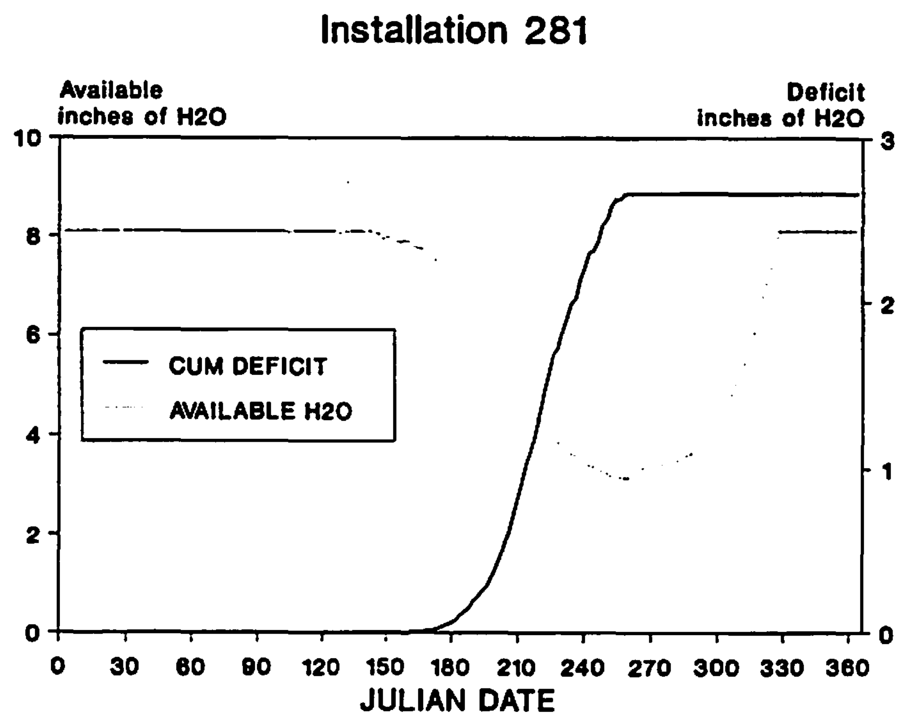


Figure 2. Various input and output variables from a soil moisture budget program for Douglas-fir installation 281, during an "average" year. Daily fluctuations are shown in the top panel and cumulative behavior is illustrated in the lower panel.

using a forest ecosystem process model, FOREST-BGC (Running and Coughlan 1988). This model uses theoretical relationships of the way in which site factors and microclimate control tree biological processes, including transpiration, photosynthesis, respiration, and carbon allocation. Details of the model's workings are presented by Running (1984a, 1984b). Inputs required by the model include daily temperature and precipitation records, starting conditions for the simulation period (snowpack, soil moisture content, and amount of carbon in leaves, stems and roots), and site characteristics (soil water holding capacity and latitude).

The model was run for a one year simulation period, using the "average" climate data for each installation. Carbon allocation was set at 2400, 50000, and 7500 kg/ha for leaves, stems, and roots, respectively; this mimics the typical distribution of carbon in a mature forest and produces a LAI of 6 m^2/m^2. Initial snowpack and soil moisture conditions were predicted by running the model for one year starting with a saturated soil and using the ending (December 31) moisture conditions as starting values for the final simulation. Output of interest included values for evaporation, transpiration, photosynthesis, and respiration.

Model outputs for installation 281 are shown in Figure 3. The upper panel shows the variation in various components of the site water budget for the year. Snowpack levels accumulate until temperatures rise sufficiently to initiate melting. At that time, soil moisture levels start increasing until field capacity is reached. At the same time, evaporation losses start to accumulate; these continue until November, when cold temperatures prevent further losses and the snowpack starts to build up again. Soil moisture content follows similar patterns as predicted by the water balance program, except that recharge in the fall is stopped when the snowpack begins to reform. Transpiration losses start occurring in late March, but slow dramatically at the end of August.

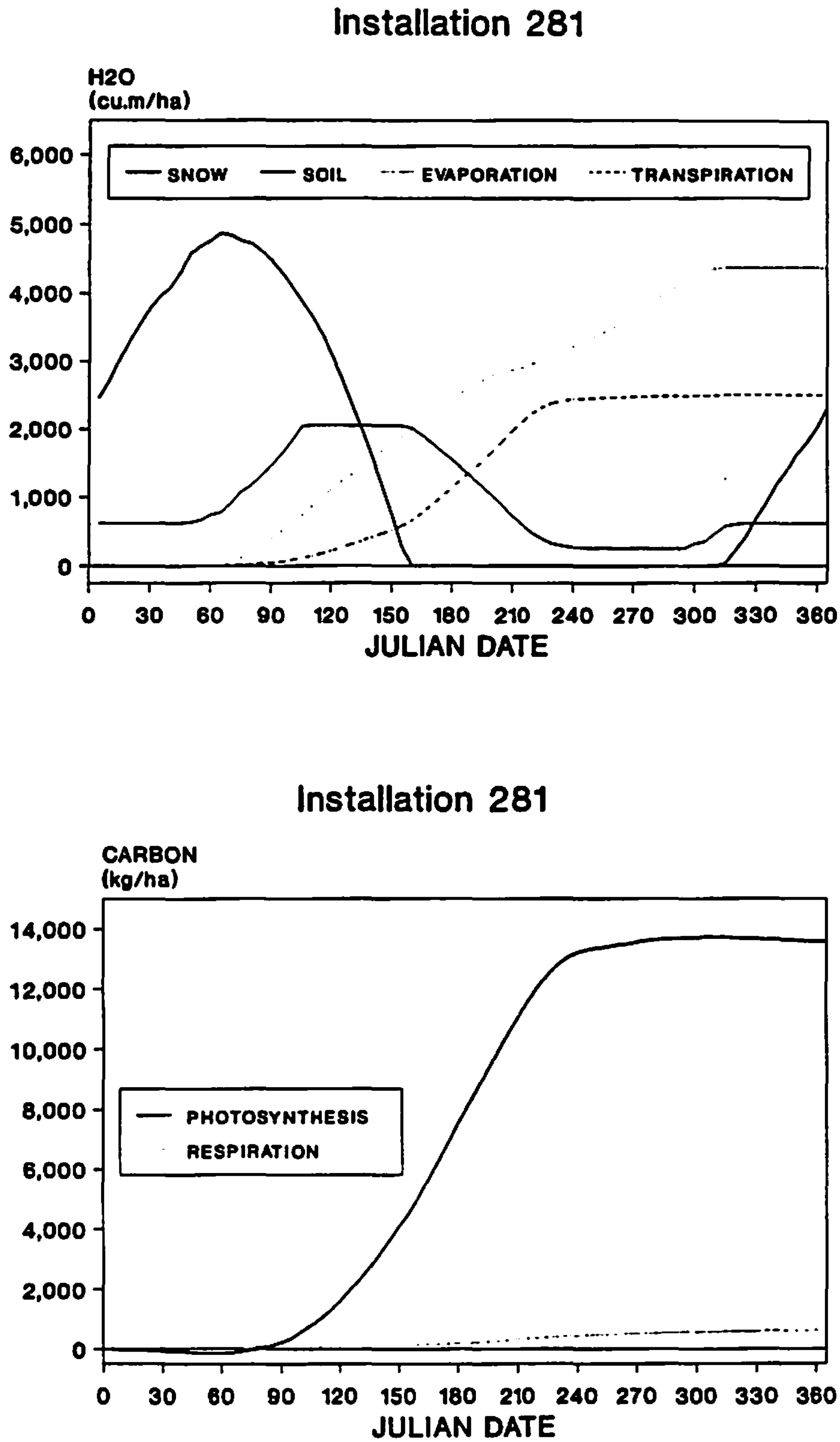


Figure 3. FOREST-BGC (Running and Coughlan 1988) model outputs during an "average" year for Douglas-fir installation 281. Snowpack, soil moisture, evaporation, and transpiration are shown in the upper panel, while photosynthesis and respiration are shown in the lower panel.

Growth processes are shown in the lower panel of Figure 3. Maintenance respiration levels stay fairly constant throughout the year, leading to a slow, steady accumulation. Net photosynthesis (gross PSN - night leaf respiration) starts accumulating in late March and slows down in late August; trends follow the same pattern as transpiration.

Results

Simple correlations between volume growth, volume response, relative response, and various process-oriented variables including Rehfeldt's genetic growth potential index, measures of site water status from the water balance program, and biological measures of potential growth from FOREST-BGC are given in Table 2. The variable definitions in Table 2 are as follows:

RESP =	six-year volume growth response to the nitrogen fertilization treatments ($ft.^3/Ac.$).
REL_RESP =	six-year relative growth response to the nitrogen fertilization treatments (%).
VOLG =	six-year volume growth ($ft.^3/Ac.$).
GENES_I =	genetic index of potential height growth (Rehfeldt 1989).
GPP =	gross primary production ($kg \cdot ha^{-1} \cdot yr^{-1}$) (from FOREST-BGC - Running and Coughlan 1988).
NPP =	net primary production ($kg \cdot ha^{-1} \cdot yr^{-1)}$ (from FOREST-BGC).
DEFICIT =	Yearly soil moisture deficit (inches) (Zahner and Stage 1966).
$MAXH_2O$ =	Soil moisture holding capacity (inches).

GENES_I, GPP, NPP, and $MAXH_2O$ all showed strong ($r \geq .7$) positive simple correlations with growth. DEFICIT was significantly negatively correlated with growth. The simple correlations (except for GENES_I) were much less for response than for growth; for relative response, only GENES_I showed significant correlation. GPP, NPP, and $MAXH_2O$ are also

Table 2. Pearson correlation coefficients and significance levels for various growth, nitrogen fertilizer response, and process model predictor variables for Douglas-fir installations in northern and central Idaho.

	RESP	REL_RESP	VOLG	GENES_I	GPP	NPP	DEFICIT	MAXH2O
RESP	1.000 0.000	0.937 0.001	0.512 0.001	0.458 0.001	0.308 0.012	0.305 0.013	-0.192 0.122	0.292 0.018
REL_RESP		1.000 0.000	0.266 0.031	0.290 0.018	0.131 0.295	0.129 0.303	-0.037 0.770	0.115 0.358
VOLG			1.000 0.000	0.747 0.001	0.713 0.001	0.709 0.001	-0.567 0.001	0.681 0.001
GENES_I				1.000 0.000	0.633 0.001	0.625 0.001	-0.529 0.001	0.673 0.001
GPP					1.000 0.000	0.999 0.001	-0.888 0.001	0.952 0.001
NPP						1.000 0.000	-0.891 0.001	0.952 0.001
DEFICIT							1.000 1.000	-0.864 0.001
MAXH2O								1.000 0.000

nearly perfectly correlated with each other, indicating that soil moisture capacity ($MAXH_2O$) essentially controls predictions of primary productivity from FOREST-BGC, at least under "average" climatic conditions. Our inputs of "average" climate had little influence on FOREST-BGC predictions of primary productivity. Further, these simple correlations suggest that while NPP, GPP, or $MAXH_2O$ should be quite useful for predicting growth, other factors explain response to nitrogen. This is confirmed in the multiple regression analysis results provided in Tables 3 through 5. We tried GENES_I, GPP, NPP, DEFICIT, and $MAXH_2O$ as candidate predictor variables for growth and response along with the variables that were useful for predicting response in part II of this report. The analysis results for predicting growth are given in Table 3. We can account for most of the variation ($R^2 \simeq .74$) in non-fertilized growth using stand density (RDO = relative density as defined in Part II of this report), GENES_I, and NPP. DEFICIT and MIN_N (mineralizable nitrogen rate as defined in part II of this report) were not significant in this model. Since NPP and DEFICIT are so strongly correlated, DEFICIT did not explain any additional variation after NPP was included in the analysis.

The model to predict absolute response is provided in Table 4. The predictor variables account for only 30% of the variation in response compared to about 75% for growth. NPP and DEFICIT are not significant predictors of response; however, RDO, GENES_I, and MIN_N are significant. NPP was significant in the growth prediction model, while MIN_N was not.

Relative response is perhaps the most direct expression of the effect of N fertilization, since absolute response is also partially influenced by the stand's inherent growth. The relative response model is given in Table 5. The same 5 predictor variables used in the previous analysis account for only about 20% of the variation in relative response, and only GENES_I and MIN_N are statistically significant.

Table 3. Analysis of variance and ridge regression parameter estimates for predicting six-year volume growth (ft.^{3}/Ac.) for Douglas-fir installations in northern and central Idaho.

DEPENDENT VARIABLE: VOLG

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
MODEL	5	7933963.86523827	1586792.77304765
ERROR	58	2857220.08770553	49262.41530527
CORRECTED TOTAL	63	10791183.95294380	

MODEL F = 32.21 PR > F = 0.0001

R-SQUARE	C.V.	ROOT MSE	VOLG MEAN
0.735226	18.2584	221.95138050	1215.61343750

SOURCE	DF	TYPE III SS	F VALUE	PR > F
RD0	1	707909.44691016	14.37	0.0004
GENES_I	1	511227.29436396	10.38	0.0021
NPP	1	1012314.66597072	20.55	0.0001
DEFICIT	1	86514.29141202	1.76	0.1903
MIN_N	1	55268.75088700	1.12	0.2939

RIDGE REGRESSION COEFFICIENTS FOR K=0.10

PARAMETER	ESTIMATE
INTERCEPT	- 42.80
RD0	955.00
GENES_I	108.39
NPP	0.0463
DEFICIT	- 1.65
MIN_N	2.35

Table 4. Analysis of variance and ridge regression parameter estimates for predicting six-year volume growth response (ft.^{3}/Ac.) for Douglas-fir installations in northern and central Idaho.

DEPENDENT VARIABLE: RESP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
MODEL	5	977173.91653092	195434.78330618
ERROR	58	2222416.93009886	38317.53327757
CORRECTED TOTAL	63	3199590.84662978	

MODEL F = 5.10 PR > F = 0.0006

R-SQUARE	C.V.	ROOT MSE	RESPONSE MEAN
0.305406	109.2972	195.74864821	179.09754626

SOURCE	DF	TYPE III SS	F VALUE	PR > F
RD0	1	102442.51917711	2.67	0.1074
GENES_I	1	401346.57337026	10.47	0.0020
NPP	1	38046.66263488	0.99	0.3232
DEFICIT	1	46663.53225738	1.22	0.2743
MIN_N	1	314051.13703241	8.20	0.0058

RIDGE REGRESSION COEFFICIENTS FOR K=0.10

PARAMETER	ESTIMATE
INTERCEPT	-100.89
RD0	374.66
GENES_I	77.86
NPP	0.0086
DEFICIT	13.23
MIN_N	- 4.29

Table 5. Analysis of variance and ridge regression parameter estimates for predicting six-year relative growth response (%) for Douglas-fir installations in northern and central Idaho.

DEPENDENT VARIABLE: REL_RESP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
MODEL	5	0.70828988	0.14165798
ERROR	58	2.93655669	0.05063029
CORRECTED TOTAL	63	3.64484657	

MODEL F = 2.80 PR > F = 0.0249

R-SQUARE	C.V.	ROOT MSE	REL_RESP MEAN
0.194326	123.7679	0.22501175	0.18180131

SOURCE	DF	TYPE III SS	F VALUE	PR > F
RDO	1	0.03152133	0.62	0.4333
GENES_I	1	0.37370103	7.38	0.0087
NPP	1	0.00414174	0.08	0.7759
DEFICIT	1	0.05274656	1.04	0.3116
MIN_N	1	0.42793961	8.45	0.0052

RIDGE REGRESSION COEFFICIENTS FOR K=0.10

PARAMETER	ESTIMATE
INTERCEPT	0.0727
RDO	0.2150
GENES_I	0.0717
NPP	2.15E-6
DEFICIT	0.0179
MIN_N	-0.0051

GI	REL RESP
1.0	.07
3.0	.21

In summary, soil moisture variables such as annual water deficit and estimates of primary forest productivity are strongly related to non-fertilized stand growth. However, they do not significantly relate to N fertilization response, which is significantly related to soil chemical characteristics such as MIN_N, AV_P, and EX_K.

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