PREDICTING PINUS RADIATA SITE INDEX FROM ENVIRONMENTAL VARIABLES

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ABSTRACT

Two hundred and ninety-nine plots of **Pinus radiata** D. Don in forests throughout the North Island of New Zealand were sampled. At each plot a site index (tree height at 20 years) estimate was obtained, and soils were sampled to determine soil depth, strength, and nutrient concentration. Climatic data were extrapolated from the nearest available station. Principal component analysis was used to reduce the large number of items of data available for each plot to a smaller, mutually independent set. A model was constructed by multiple regression analysis which related site index to this set of variables. The model has a standard error of 2 m around a mean site index of 29.2 m, and predicts increasing site index with increasing rainfall, nutrients, topsoil depth, and soil penetrability, the optimum average annual temperature for growth being 12°C and the optimum soil pH 6.

Validation of the model on a New Zealand-wide set of plots, subjectively chosen to be in extreme conditions, showed that it generally behaved reliably. It did, however, overpredict growth for an unusual forest on shallow slopes receiving 4000 mm of rainfall per year.

INTRODUCTION

Fenton & Dick (1972) showed that profitability of afforestation for the export log trade was greatest on sites of high site index. This was due partly to the greater productivity of such sites and partly to the shorter rotations which were possible. Recently, work on a general silvicultural model has reaffirmed that the level of site productivity is one of the most important variables in determining over-all profitability, and so it is vital that investment in forestry is directed towards land of high productivity.

Guidance on the likely growth of *Pinus radiata* on an unplanted site in New Zealand is limited. Foresters use local experience, local models (C. J. Mountford pers. comm.), or may adapt the principles of the general model developed by Jackson & Gifford (1974), as for example in the King Country Land Use Study (1978). Estimates of likely productivity are therefore necessarily very approximate for many new projects. Moreover, the forester is often unable to produce data of sufficient quality to cause a local authority to modify a planning decision to restrict forestry operations as many such New Zealand authorities are attempting to do (Rockell 1980).

The forester therefore requires a reliable indication of potential site productivity. As Hagglund (1981) in a recent review of the subject has stated, site index (height of dominant trees at a determined age) is a commonly accepted measure of site quality almost all over the world. It is usually reported to be well correlated with volume growth and relatively independent of silvicultural practices. More direct measures of salable production such as standing volume or volume increment are not independent of silvicultural practice, stand condition, or age at determination. These variables may interact with site characteristics and be correlated with regional differences in such a way as to make modelling very difficult.

This paper deals with a recent attempt to relate the site index (SI) of *P. radiata* (mean top height at 20 years) on permanent plots distributed throughout the North Island of New Zealand, to environmental variables such as soil and climate.

METHODS

Site Selection

The computer-based Permanent Sample Plot system (McEwen 1979) was interrogated to locate plots meeting certain criteria. The plots selected carried *P. radiata* stands at approximately 20 years of age. In 57% of the plots top height (height of the 100 largest-diameter trees per hectare) had been measured at 20 years of age. In a further 27% there was no measurement at exactly age 20 but two measurements within 3 years either side. In the remainder, 10% were between 17 and 20 years of age, 5% between 15 and 17 years of age, and 1% were less than 15 but more than 12 years old. These last were included only to provide a greater number of plots in some of the younger forests.

In order to minimise possible soil chemistry changes since the stands reached the site index age, maximum age was restricted to 30 years. Thinning should not have occurred in the previous 5 years – Madgwick *et al.* (1977) have shown that significant amounts of nutrients are returned in trimmed branches at thinning.

The selected plots were further screened in order to achieve a balanced distribution by soil type and climatic zone around the North Island. Because most forests in the Auckland region receive repeated applications of phosphorus fertiliser to correct endemic phosphorus deficiency (Ballard & Will 1978) and all coastal sand forests are grown in the presence of tree lupin which supplies considerable nitrogen (Mead & Gadgil 1978), this selection of plots inevitably reflects growth as affected by current management practice. Three hundred and sixty plots were visited, and the location of the main forests involved is indicated in Fig. 1.

After some initial modelling work on the data collected from these North Island sites, a further set of sites was subjectively chosen from throughout the country to represent extreme conditions and constitute a validation set. These sites are also indicated in Fig. 1, with the forest name followed by (v). Field and laboratory procedure was the same for these sites as for the main survey.

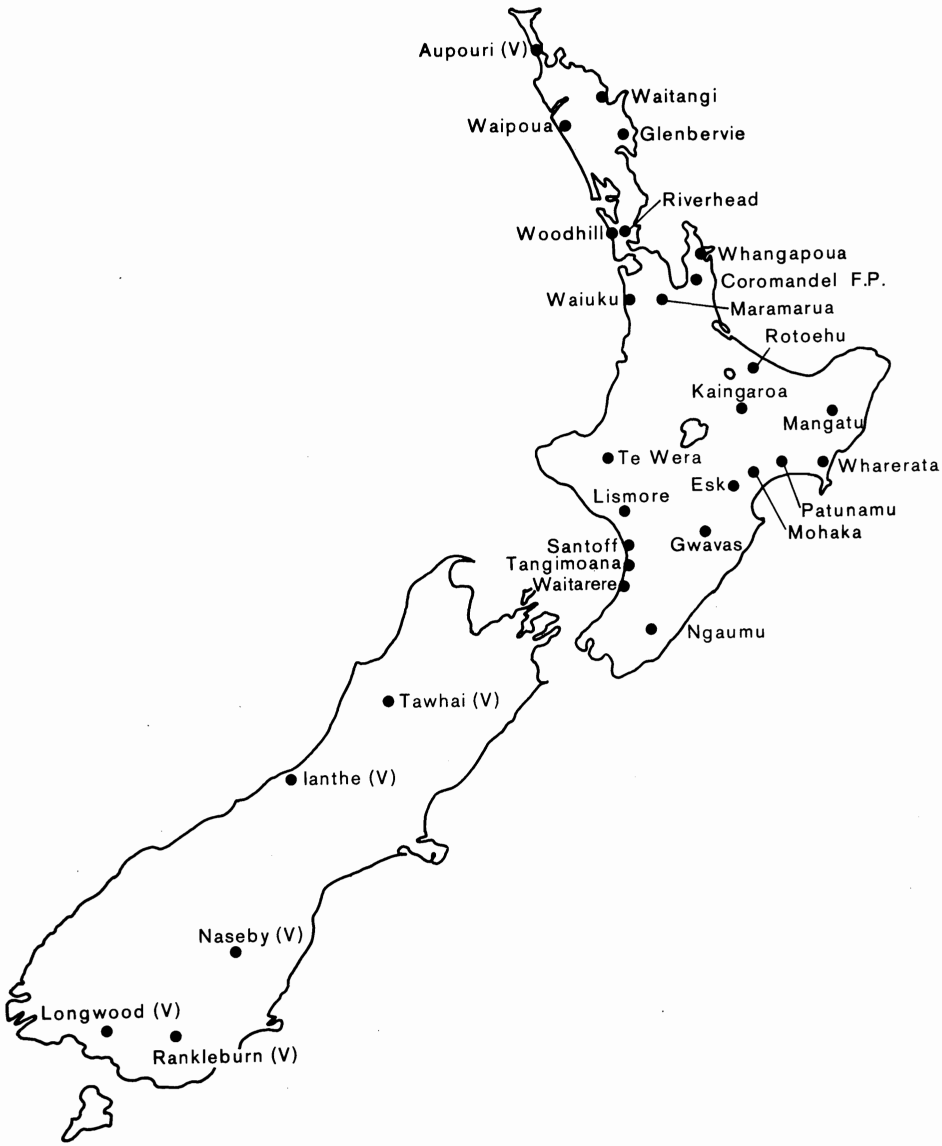

FIG. 1—Location of the main forests visited during the initial survey and during the validation survey (v).

Field Procedure

At each plot, 10 small pits were excavated with spade and auger to 1 m to determine soil variability within the plot. Some plots in which soil type varied markedly were rejected at this stage – e.g., a plot in a recent sand forest, partly on recent windblown sand and partly on an older peaty phase. Two hundred and ninety-nine plots were ultimately accepted.

Litter depth and A horizon depth were measured at each exploratory pit. Soil samples were collected from the A horizon, and from the bottom of the A to 60 cm. A pit which represented the median of soil variation was enlarged to at least 1 m in depth, and a pedological description was made using the methods of Taylor & Pohlen (1970). Soil moisture status was assessed visually and recorded. A small hand-held spring plunger was used to measure soil resistance to penetration to a maximum of 50 kg/cm^2; for each horizon 10 values were taken and averaged. Raw data have been recorded by Gibson & Healy (1982).

Soil Analyses

Soil chemical and physical analyses were made using the methods of the New Zealand Soil Bureau (1972). Samples from the A horizon were analysed for percentage of fines (silt and clay), pH, percentage nitrogen, percentage carbon, Bray and Olsen phosphorus, and exchangeable cations (potassium, magnesium, and calcium). Subsoil samples were analysed for the same set of elements (minus carbon and nitrogen).

The resistance to penetration in each horizon was used to calculate the highest resistance in every 10-cm zone down to 60 cm.

Climatic Data

Climatic data are seldom collected at plot sites. Most, but not all, forests visited collect rainfall and temperature data at least during the fire (summer) season, usually at the headquarters. Only some of the forests maintain full meteorological stations. Forest headquarters, moreover, are sometimes deliberately placed in the most climatically favourable position for human habitation and can be much warmer than the forest as a whole. Some extrapolation of climatic data from the full station nearest the plot was therefore inevitable and it was decided to explore by principal component analysis the basis for this on as wide a range of data as possible.

Climatic data were extracted for 154 stations in the North Island for which 30-year normals were available (New Zealand Meteorological Service 1978). Twenty-two of these are full stations on forest. Monthly mean maximum and minimum temperatures and total monthly rainfall were used. Other potentially relevant data such as sunshine hours, open pan evaporation, and windrun are not recorded at a sufficiently large number of stations to be useful.

Calculation of Site Index

If the plot had not been measured for height at exactly 20 years of age, site index was calculated using the appropriate regional height/age relationship (Burkhart & Tennent 1977). Where there were several measurements at around 20 years the average predicted site index was used. It might be objected that the use of regional curves for adjustment removed part of the variation it is intended to study. However, prediction differences between curves are very small when used to predict SI over short periods.

Statistical Methods

The data available for analysis consisted of site index (as the dependent variable), 18 soil physical and chemical variables, and a set of climatic data as yet unlinked to the soil data set. Before using the data in multiple regression analysis it was thought desirable to simplify and reduce the number of independent variables and remove as much multicollinearity between the variables as practically possible. The Genstat (Lawes Agricultural Trust 1980) principal component routine (PCA) was used to achieve this objective. The six soil resistance values were initially analysed separately and then combined with the other 12 soil variables. The monthly mean minimum and mean maximum temperatures and monthly rainfall, with station altitude, latitude, and longitude, were also analysed. From the results of these analyses a set of variables was chosen and used in multiple regression analysis. Page (1976) used a similar procedure.

RESULTS

A summary of the data showing the range of sites covered is given in Table 1. A very clear result was given by PCA of soil resistance. Resistances at all depths were highly and positively correlated with the first component which in itself accounted for 80% of the total variation. The second component, with 11% of the variation, showed a contrast between the resistances in the upper 20 cm and the lower 20 cm (40–60 cm). It seemed very likely from inspection of the principal component scores that the first component would be highly correlated with soil texture. The original data set was therefore combined with the other soil variables, but PCA on the combined set did not give such clear results. With 35% of the over-all variation, the first component was composed largely of subsoil pH and phosphorus contrasted with percentage fines and penetration resistance. This component seems to reflect the variation between, on the one hand, recent coastal sands typically high in phosphorus and pH and low in fines and, on the other, old clays, with pumiceous soils having intermediate values.

TABLE 1—Mean, maximum, and minimum of some surveyed traits

Trait	Mean	Maximum	Minimum
Site index (m)	29.2	37	19
Average temperature (°C)	12.3	15.7	9.4
Annual rainfall (mm)	1450	2300	870
Soil			
A horizon depth (cm)	11	47	0
Silt and clay (%)	49	99	1
A horizon N (%)	0.28	1.05	0
A horizon Bray P (ppm)	20	120	1
A horizon pH	5.6	8.2	4.2

The second component (15% variation) was composed of percentage nitrogen, percentage carbon, and cations at both soil depths, while the third (11%) was largely phosphorus. The fourth component (10%) was composed largely of pH and subsoil calcium. A horizon depth and litter depth were strongly correlated with the fifth and sixth components respectively (5% each).

Since the separation of terms is not completely clear, an element of subjectivity must enter into independent variable selection. The most significant part of each component was chosen as an independent variable. Average resistance to penetration was chosen to represent the first component, the scaled sum of nitrogen and cations the second (referred to as "soil fertility"), Bray phosphorus the third, and pH the fourth. Soil resistance contrast, A depth, and litter depth completed the set of soil variables.

Each monthly maximum and minimum temperature was strongly correlated with the first principal component (55% variation) resulting from PCA of climatic data. Most monthly rainfalls were weakly and negatively correlated, but early summer rainfall was more strongly correlated. Altitude was very strongly negatively correlated, but neither latitude nor longitude were particularly well related. Rainfall was clearly the major factor in the second component (24% variation). Altitude, latitude, and longitude were not well correlated with this vector. The third component (14%) showed a strong contrast between summer maximum and winter minimum temperatures. It appeared that suitable independent variables were average annual temperature which could be adjusted by the altitude difference between plot and station (at 0.6°C per 100 m, i.e., the adiabatic lapse rate), annual rainfall (with no altitude adjustment), and an index of continentality (the sum of the summer maximum temperatures minus the sum of the winter minima – from the third component). These variables were therefore calculated for each plot from the nearest station. Local rainfall stations were used where appropriate.

An initial multiple regression analysis of site index against the above 10 variables was made. When site index and each variable were graphed, various curvilinear relationships were clearly suggested and tried in regression analyses. The apparent optima for pH and temperature were determined iteratively in small steps (0.5 units of pH and 0.5°C), selecting the optima with the highest 't' value. The interaction of soil strength and contrast appeared to be the simplest and most significant way to express soil penetrability. Litter depth and the index of continentality were not significantly correlated with the variation in site index. Subsequent inspection of predicted and actual site index showed two types of site were not well predicted – plots in recent coastal sand forest affected by sea wind exposure, and plots in North Auckland that had received no phosphorus fertiliser. For the latter, differences in soil phosphorus were not sufficient to explain the differences in site index brought about by fertiliser application (Hunter & Graham 1982). Plots with these characteristics (11 in all) were excluded from further analyses.

The final regression surface (selected because on balance it explains the greatest amount of variation, is the most compact, and has the highest 't' values associated with individual terms) is given in Table 2. The standard error of the model is 2 m. The regression accounts for 57.7% of the total variation.

The correlation matrix is given in Table 3 and shows that the assembling of complex variables based on principal component analysis was successful in preventing multicollinearity between environmental variables.

TABLE 2—Multiple regression of site index against environmental variables

	Coefficient	Standard error	t
Constant	—16.78	4.41	3.8
1. Departures from pH 6	— 0.70	0.20	3.5
2. Departures from 12°C	— 0.78	0.16	4.9
3. Log soil fertility*	+ 1.33	0.23	5.8
4. Log A depth	+ 0.86	0.17	5.1
5. Average resistance × contrast*	— 0.001	0.0002	5.1
6. Log annual rainfall	+ 5.26	0.61	8.6
7. Log Bray phosphorus	+ 0.53	0.13	4.2

* See Appendix 1 for full definition of terms

TABLE 3—Correlation matrix

1. pH 6 (abs departure)	1							
2. 12°C (abs departure)	+0.044	1						
3. Log soil fertility	—0.044	—0.325	1					
4. Log A depth	—0.224	—0.198	+0.447	1				
5. Resistance × contrast	+0.005	—0.059	+0.267	+0.328	1			
6. Log annual rainfall	+0.051	—0.049	+0.211	+0.472	+0.133	1		
7. Log Bray phosphorus	—0.132	—0.055	—0.269	—0.150	—0.104	—0.119	1	
	1	2	3	4	5	6	7	8

DISCUSSION

Studies of this nature cannot explain the processes involved in growth. They can, however, help in hypothesis formation about those processes.

The chosen set of variables which covary with site index do so in such a way that no forest represented in the initial survey data set had an average actual site index which differed by more than 3 m from the average prediction (Table 4). The same is true for most of the forests visited in the validation exercise (Table 5). It was not true for the cold (8°C average annual temperature) and dry (600 mm annual rainfall) forest of Naseby. However, since both actual and predicted site indices are very low, the over-prediction in site index was not large enough to cause a mistaken evaluation of the forest site potential. Neither was it true for the very wet (4000 mm) gently sloping terrain at Ianthe where site index was overpredicted by 6.7 m – a serious error in terms of evaluating site potential. A drier (2000 mm) sloping site on the west coast (at Tawhai) was predicted accurately.

TABLE 4—Comparison of observed and predicted forest site index for the more intensively sampled forests

Forest	Number of plots visited	Average site index	
		Observed	Predicted
Pumice forests			
Kaingaroa	55	30.6	30.4
Esk	28	30.8	31.7
Mohaka	4	32.2	31.5
Rotoehu	4	33.8	31.7
Sand dune forests			
Woodhill	27	26.1	26.9
Waiuku	12	26.1	27.1
Santoft	14	25.4	26.2
Waitarere	11	26.1	25.9
Tangimoana	6	26.0	25.0
Auckland forests			
Whangapoua	4	30.2	28.9
Waipoua	5	29.8	28.7
Glenbervie	14	29.3	29.8
Coromandel	3	27.0	27.2
Waitangi	8	28.6	27.4
Other forests			
Mangatu	13	30.1	30.8
Te Wera	21	32.6	31.8
Ngaumu	16	28.9	28.1
Gwavas	20	27.6	29.1
Patunamu	8	32.9	31.7
Wharerata	7	32.7	33.8

Thus, with certain limitations, forests (or large blocks of land) can be allocated with reasonable confidence to the categories used in the King Country Land Use Study (1978) – high site index (greater than 29 m), medium (25–28 m), and low (less than 25 m). These groupings have considerable utility for management practice.

However, within a forest, individual plots were sometimes badly modelled. While some of these prediction errors were probably due to causes such as recent improvements in height growth (resulting from, for example, better establishment), climatic data error introduced by using the nearest available station, and height measurement error in the field, there remains a fairly large unaccounted variation within forests. Further work on microsite variables (slope, aspect) may help to reduce this variation, although the effect of these variables can differ markedly between forests. For the present the model is best seen as predicting the average site index to be expected on an area of land greater than 200 ha.

The model predicts that site index is greatly affected by rainfall. The forest of Naseby was included in the validation set to test the prediction that growth would be

TABLE 5—Comparison of observed and predicted forest site index in the validation set

Forest	Number of plots visited	Average site index	
		Observed	Predicted
Aupouri	10	24.3	23.3
Naseby	2	14.0	18.4
Longwood	3	24.0	22.7
Rankleburn	5	22.1	24.7
Tawhai	4	24.1	24.8
Ianthe	5	24.5	31.2

reduced by low rainfall. The logarithmic transformation of the rainfall term means that increments of rainfall have progressively less effect on predicted site index. Nevertheless the model does not allow for a reduction in growth resulting from extremely heavy rainfall. The forests of Tawhai and Ianthe on the west coast of the South Island were selected to test this aspect. Tawhai growth was correctly predicted but Ianthe growth was grossly overpredicted. Jackson & Gifford (1974) had an interaction between soil depth and rainfall in their model, specifically to allow for the depressing effect of high rainfall waterlogging the soil. Attempts to fit such a term to all the data were unsuccessful and the five Ianthe plots are insufficient in number to outweigh the rest of the data.

The reduction in growth with decreasing annual temperature is understandable. A decrease with increasing temperature is less understandable, particularly in view of the successful *P. radiata* plantations in more northerly Australian latitudes. Jackson (1967) documented one other example with another species. Rook & Corson (1978), however, have shown that, in a controlled environment, the optimum temperature for net photosynthetic gain of *P. radiata* was 10°C. Above that temperature respiration began to increase and exceeded photosynthesis at 25°C. New Zealand is a difficult place to test this finding since all the areas with temperatures warmer than the apparent optimum lie in the endemically nutrient-deficient areas of the North Auckland Peninsula. Other studies, for example Cown (1980), with wood properties, have been affected by this confounding. Although other soil-derived terms in the model, such as Bray phosphorus and the term in soil fertility, are expected to remove the variation due to low soil fertility, in North Auckland they may not completely do so. However, the sand forest of Aupouri was specifically included in the validation set to test growth on the warmest site in New Zealand (15.9°C mean annual temperature). Growth was predicted to be less (by approximately 2 m) than the other more-southerly sand forests and does in fact seem to be so.

The soil collected in this survey had been exposed to the influence of pine tree growth for approximately 20 years. The changes in particular soil chemistry which may have occurred could mean a difference between predictions for planted and unplanted land when that land was similar in all other characteristics. Few workers in this field have been able to resolve this problem. Page (1976) studied changes with time under tree species on a narrow range of soil types in Newfoundland and adjusted his data accordingly to represent the preplanting state. Will & Ballard (1976) concluded that, over a range of soil types, changes in soil characteristics under pine trees are inconsistent in magnitude and direction. In this model, since the terms are transformed logarithmically, changes from initial soil chemistry values would have to be of an unlikely large magnitude (much greater than those observed in repeated soil analyses of routine experiments – Hunter unpubl. data) to have a major effect on the prediction of site index.

Variations in soil acidity have only a small effect on predicted site index. Compact soils or those with a very high degree of contrast in resistance in the top 60 cm reduce predicted site index. The practical implication that height growth could be increased by cultivation of such soils is confirmed (Hunter 1981) by experimental evidence. Increases in the value of the terms constructed from soil chemical analyses (soil fertility and Bray phosphorus) and A horizon depth, all cause increases in the predicted site index. Within the range of the collected data each one is capable of varying site index by up to 3 m, with greatest changes associated with low values. Although experimental evidence confirms that increases in the supply of some nutrients when they are at a low level increase height growth (for phosphorus – Hunter & Graham 1982; nitrogen – Hunter & Hoy 1983), the implication that further small increases could be achieved by increasing the supply of nutrients when they are at an average-to-high level in the soil is almost certainly incorrect since Woollons & Will (1975) showed that application of a mixed fertiliser containing nitrogen, phosphorus, potassium, calcium, and magnesium to trees on the pumice plateau did not affect height growth. Moreover, the exact relationship of site index to very low values of soil nitrogen and phosphorus has been modified by the regional fertilisation practices where either is deficient. Insufficient plots exist in the affected regions to construct a model of this type while entirely eliminating the complication of the tree growth being enhanced by management practice. It has been suggested that the three terms act in some way as a surrogate for moisture retention in the soil. It is difficult to see how this could be so in any simple way since each one is highly independent of the others. However, the possibility exists of further simplifying the model and must be explored.

Over-all, the model presented in this paper has broad similarities with other models constructed for *P. radiata* site index (Czarnowski *et al.* 1971; Schlatter *et al.* 1982; T. Booth pers. comm.), although there is considerable variation between workers in the independent variables selected. Total rainfall is important in the Chilean model (Schlatter *et al.* 1982) with an apparent optimum of 2000 mm per year. It is also important in the recent Australian model (Booth pers. comm.). Soil chemistry (phosphorus and cations) is important in both the recent and the older Australian appoach (Czarnowski *et al.* 1971). Phosphorus is not significant in the Chilean model but nitrogen and potassium are. Soil texture is important in all models, although measured differently (bulk density in the Chilean model) and sometimes with a different emphasis (available water capacity in the recent Australian model). Temperature effects are handled by altitude in the recent Australian model and by latitude and longitude in the Chilean model.

Hagglund (1981) pointed out that most workers prefer not to use soil chemistry data in models of this type because such data are not freely available to practitioners. If, however, such models are used as a guide to land purchase it would seem dangerous and inadequate to rely for information on an easily measured but indirect and less well-correlated measure of soil fertility when the cost of soil analysis would be an insignificant proportion of the total capital cost. In New Zealand, moreover, sufficient information of a reasonable quality would be available to practitioners for most soil types from published information and local soil analyses to enable a reasonable first approximation to be made.

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APPENDIX 1

DEFINITION OF THE COMPLEX TERMS USED IN THE MODEL

1. Departures from pH 6	Absolute (plot pH -6)
2. Departures from 12°C	Absolute (mean annual temperature -12)
3. Log soil fertility	Natural log $\times$ (100 N% + (10 Ex Ca + 10 Ex Mg + 100 Ex K) me %)
4. Log A depth	Natural log (1 plus plot A horizon depth in centimetres)
5. Average resistance $\times$ contrast	Average soil resistance to penetration (kg/cm^2) multiplied by the average resistance in the top 20 cm minus the average in the bottom 20 cm (40-60 cm)
6. Log annual rainfall	Natural log of annual rainfall
7. Log Bray phosphorus	Natural log (Bray extractable phosphorus ppm)