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EMPIRICAL MEASUREMENT OF ENVIRONMENTAL GRADIENTS IN ECOLOGICAL SURVEYS

Summary: Soil temperature, soil moisture and soil fertility were determined empirically at 63 predominantly hill sites in the South Island, New Zealand. Soil temperatures were measured at a depth of 0.5 m in four seasons and gave a standard deviation of mean annual temperature between sites of 2.2 °C. Soil moisture levels, as available water in a 0-0.5 m profile, measured seasonally, gave a standard deviation between sites of 49 mm water. Soil fertility was measured in a common environment as yield of a test species grown in each soil expressed as a percentage of the yield in the same soil given complete nutrients. On this scale the standard deviation between sites was 19%. The trial showed that these environmental factors can be empirically measured in surveys.

Keywords: Environmental factors; gradient analysis; temperature; moisture; soil fertility.

Introduction

The geographic location of a site is defined by the co-ordinates latitude, longitude and altitude. In the same manner a co-ordinate system is needed by ecologists to define the 'location' of a site within the environmental domain of multiple gradients. Such approaches to environmental ordination, or direct gradient analysis, have been attempted for a number of world plant formations (e.g. Holdridge, 1947; Crocker and Major, 1955; Whittaker, 1956, 1967; Loucks, 1962; Waring and Major, 1964; Fonda and Bliss, 1969; Peet, 1981). In these there is a general consensus that moisture availability is one of the principal environmental factors (Taylor and Pohlen, 1962; New Zealand Soil Bureau, 1968; Fonda and Bliss, 1969; Watt, 1977), though a variety of expressions for it have been suggested (Holdridge, 1947; Thornthwaite and Mather, 1955). Temperature has also been considered as an important factor (Zotov, 1953; Holmes and Robertson, 1959; Waring and Major, 1964; Cleary and Waring, 1969; Aldridge, 1977; Austin *et al.,* 1984).

Most authors, however, have used indirect factors such as altitude, aspect and slope (Whittaker, 1967; Austin and Cunningham, 1981; Peet, 1981), which confound geographic and environmental co-ordinates. Whilst acknowledging the utility of such indirect measures within a limited area, there is a trade off between their ease of measurement but indirect ecological nature, versus direct measurement of the environmental factors.

In previous publications we have suggested that the broad patterns of New Zealand vegetation, both natural and agricultural, are related to the three environmental gradients of temperature, moisture and soil fertility (Scott, 1979 a,b; Scott and Groves, 1982). This paper describes attempts to obtain simple, single estimates of these factors for sites within a limited area - in this case a range of Canterbury hill environments.

The annual cycle would seem to be the most natural integrative time period for any measurement. Depending on the purpose of the investigation there may need to be some adjustment of values for the particular period to make them comparable with the longer term averages.

The damping and integrative effect of soils on temperature make it possible to characterise the annual mean temperature of a site by a single spot measurement at depths greather than 15 m, or by averaging four spot measurements taken at depths of 0.5-1 m at three-monthly intervals (USDA Soil Conservation Service, 1975).

Although annual rainfall is the most readily available measure of moisture, its effect on soil moisture and plant growth is strongly influenced by evaporation, soil texture and depth, storage capacity, and topography as it influences water table and drainage. These considerations have led to successively more refined measurements of soil moisture status, such as days of deficit, or to complex computer simulations including variable plant responses to different moisture tensions. Unfortunately, the closer these approaches get to reality, the greater the resources required to measure the variables and consequently the fewer sites for which the appropriate measurements have been made. Because of these difficulties, the present study investigated whether periodic sampling of soil moistures at the same time as temperature measurement was a feasible approach.

The least satisfactory aspect of previous work is the handling of the nutrient regime. This is an important consideration in the relationship between natural and agricultural systems, since fertility is often the easiest factor to modify.

The standard approach to soil fertility is to use soil chemical properties, but there is no general fertility index integrating such soil chemical properties. Most analyses are used only to identify a few limiting nutrients in particular situations. The testing of any such general fertility index based on chemical properties would generally involve collection of soils into a common environment and measurement of yields of a common test plant (e.g. Widdowson and Wells, 1968; Foggo and Meurk, 1983).

For survey purposes, or to compare a number of sites or treatments, we suggest an alternative to chemical assay. 'Soil fertility' is basically a plant-orientated concept. Following the tradition of Jenny (1941), of varying one environmental variable while holding others constant, we suggest that plant growth in an unamended soil relative to that of a fertiliser non-limiting, amended control could be used as an index of soil fertility, i.e. the ratio, expressed as a percent, of unamended to amended plant yields. There are two possibilities for the fertiliser non-limiting control. One would be to relate plant growth in each soil to the fertiliser amended control of the same soil. This should isolate the effect of nutrients from other characteristics (e.g. physical properties) of the particular soil. These other properties are. likely to vary among soils. The second possibility would be to use the highest of the fertiliser-amended yields in a range of soils estimated at one time as the control. This would have the virtue of including a comparison between soils, but have the disadvantage of confounding many soil properties, besides nutrients, in the concept of soil fertility. A comparison of the two indices would indicate the relative importance of nutrient limitation relative to other soil properties. The value of either is that it would be relatively easily determined by experiment. For comparing a range of sites this provides a quantitatively continuous variable which may be used as a fertility factor.

Methods

Sites

Sixty-three sites were used, mainly on unfertilised hill soils in the Mackenzie Basin of the South Island, New Zealand, but including some from elsewhere in Canterbury province. Sites were chosen for local topographic uniformity, accessibility and apparent contrast between them in the three factors. They ranged in altitude from 0 to 2000 m, with different slopes and aspects.

The sites were established between 9 February and 4 March 1981 by installation of access holes for soil temperature measurement, collection of soil samples (see later sections), and recording of site characteristics and present vegetation. The sites were revisited at approximately three-month intervals for the next year during the periods 28 April-6 May 1981 (autumn), 27 July-11 August 1981 (winter), 25 October-3 November 1981 (spring), and 28 January-1O February 1982 (mid-summer), for measurements of soil temperature and moisture. The sites were visited in the same sequence on each occasion. The dates were chosen to correspond to the approximate annual maximum, mean and minimum temperatures based on long-term records from the few regional meteorological stations in the area (Coulter, 1975).

Soil temperature

Soil temperature was measured at a depth of 0.5 m in 3 access holes, 1-2 m apart, at each site. In each hole a hollow metal tube of c. 1 cm diameter was placed in contact with the soil, water-filled, and attached to a narrow, stoppered, protruding alkathene tube with low heat conduction properties. Temperatures were measured by inserting a thermistor probe down the tube on each occasion and equilibriating for a few minutes. Instrument accuracy was ± 0.2∞C. The annual mean temperature and amplitude were determined by regression analysis on the 15 points (5 sampling dates x 3 reps) assuming a cosine annual temperature cycle.

The rocky nature of many of the soils limited the standard sampling depth to 0.5 m. Preliminary investigations had established that temperature variations at 0.5 m were generally less than 0.4 ∞C over an 8-12 hr daylight period and hence time of day was not critical (an important consideration when many sites have to be visited in a short period). Records from official meteorological sites indicate that 0.5 m soil temperatures could change at rates of 0 to 0.5 ∞C per week.

Soil Moisture

For soil moisture, 3 soil samples were taken from most sites on each temperature sampling occasion, with a 2.5 cm diameter soil corer, in 10 cm increments down to 0.5 m, and combined for determination of gravimetric soil moisture. From the samples, soil moisture and bulk densities were estimated. On rocky sites, samples of fine material were dug for gravimetric moisture assessment and independent measurements were made of stone contents and bulk density. Pressure plate determinations were made in the laboratory of the wilting point at 15 bar for each depth increment. From the combined data the amount (in millimetres) of available water in the 0-0.5 m soil profile was calculated for each site on each sampling occasion. The annual mean and amplitude of available water were determined by regression analysis assuming a cosine annual cycle.

Soil fertility
At each site, soil was collected from a depth of 1-20 cm. Air-dry soil was sieved (5 mm) to remove large roots and stones and mixed thoroughly before weighing into 1150 g lots per plastic pot. A sample of each sieved soil was analysed chemically (MAF quick tests). Oat *(Avena sativa)* was used as the test species because of its response over a range of soil fertilities, and was sown in May 1982. The two treatments were the unamended soils and a nutrient non-limiting treatment, in which the soils were given nutrient solution twice or thrice weekly to more than double nutrient supply required for the expected growth rate (based on 'Foliar Nitrophoska' plus sulphur supplementation at a rate giving 22 mg N, 5 mg S, 4 mg P, 21 mg K/pot/week and other macro- and micro-nutrients). The pots were sunk in soil outdoors at Lincoln near Christchurch, and kept well watered. There were 4 replicates of each treatment with guard strips between blocks. Shoots were harvested in October, at which time the mean weight of fertilised treatments was 2.7 g (dry weight)/pot. The ratio (expressed as a percentage) of yield in the unamended soil relative to the corresponding yield in the fertilizer-amended soil was used as one soil fertility index. The second alternative expressed the ratio of the yield in the individual unamended soil to the mean yield of the top 5% of all amended soils - the 5% being a compromise between the need to allow for measurement variability and the absolute highest measured yield.

Results

Soil temperature and moisture
Over the 63 sites, the mean annual temperature at 0.5 m was 9.8 ∞C with standard deviation 2.2 ∞C (Table 1). Seasonal differences between sites were greatest in summer and least in winter. The within-site standard error for particular sampling times averaged ± 0.3 ∞C.

There was wide variation between sites in available water (Table 2); the standard deviation between sites was 49 mm around an annual mean of 76 mm water. Whilst the mean available water varied with season, the relationship between sites remained similar.

Table 1: *Annual and seasonal variation in soil temperatures (^{o}C) at 0.5 m depth among 63 sites in the South Island, New Zealand.*

Period	Mean	Standard Deviation
Seasonal		
Summer (February 1981)	16.4	5.6
Autumn (April)	9.7	3.9
Winter (July)	3.6	2.7
Spring (October)	9.8	4.5
Summer (February 1982)	15.3	5.6
Annual		
Mean	9.8	2.2
Amplitude	6.1	1.3

Table 2: *Annual and seasonal variation in available soil moisture (mm water) between 0 and 0.5 m depth at 63 sites.*

Period	Mean	Standard Deviation
Seasonal		
Summer (February 1981)	43	60
Autumn (April)	81	59
Winter (July)	107	54
Spring (October)	81	52
Summer (February 1982)	40	54
Annual		
Mean	76	49
Amplitude	35	18

Soil fertility
The distribution, using the first index, showed that oat yields for the individual unamended soils ranged from 8% to 66% (mean 27%) of those from the top 5% yields of nutrient amended soils (Table 3, Fig. 1). This indicated the generally low fertility status of the soils. Also only a few of the plant yields approached the 100% (horizontal dotted) nutrient non-limiting line. This indicates that there were soil differences other than nutrients which affected plant yield when soils were in a common temperature and moisture environment.

Using the second index of plant yields on soils relative to the nutrient amended yield of the same soil, gave a higher mean value of 43% (Table 3), and a distribution shown by the relationship to the sloping dashed lines of Fig. 1. The standard deviation to mean ratio between sites was similar for the two indices.

There did not appear to be any relationship between either soil fertility index and soil type where nominally the same soil type was sampled on three or more sites (Fig. 2).

There was only a weak relationship between both indices and soil chemical properties. For the index using individual soil control a regression analysis only accounted for 4% of the variation. For the 'top' control index the two significant factors selected by stepwise multiple regression were, in order, pH and Olsen-extractable phosphate, which collectively accounted for 48% of the variation.

Table 3: *Variation in two soil fertility indices (as % of nutrient amended) and some soil chemical properties at 63 sites.*

	Mean	Standard Deviation
Soil fertility index, relative to		
1. Top 5% of all soils	27	11
2. Individual soil	43	19
Soil chemical properties		
pH	5.1	0.6
Nitrogen (%)	0.23	0.09
Carbon (0/0)	2.8	1.1
Phosphate total (%)	0.072	0.026
organic (ppm)	624	394
Olsen (ppm)	7.0	8.6
Sulphur (ppm)	3.5	3.5
Potassium - exchangeable (%)	0.38	0.26

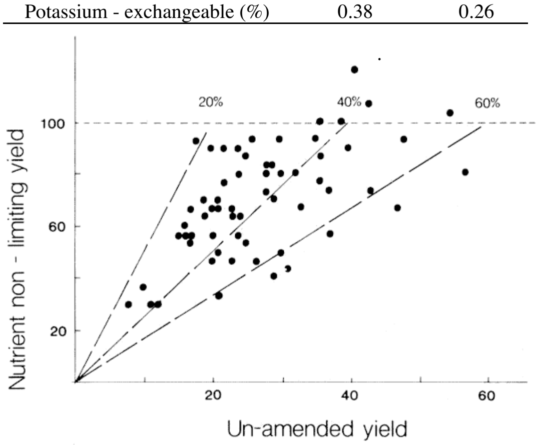

Figure 1: *Soil fertility indices. The first index is given by the ratio of unamended yield to maximum (top 5%) nutrient non-limiting yield (horizontal dolled line). The second index is the ratio of unamended yield to individual nutrient non-limiting yield (compare with dashed lines corresponding to 20%, 40% and 60% of the individual nutrient non-limiting yields).*

Variation between sites

The distribution of sites in terms of soil temperature, moisture and fertility is presented in Figure 2. The mean annual temperature scale has been inverted so that the vertical scale can also be envisaged as an approximate altitudinal scale. The initial impression is of the relationship between temperature and available water. While such a correlation probably exists, in the present case it is more related to the set of sites sampled. As the measurements were made in generally lower rainfall environments and over a wide altitudinal range, they probably include the coolest and driest environments in New Zealand. Lowland sites elsewhere in New Zealand would show higher mean temperatures and higher available soil moisture levels.

The variability in fertility index is largely related to local soil-forming factors which are not themselves related to soil temperature and moisture values. Hence the higher fertility sites are scattered throughout the range of temperatures and moisture levels.

No attempt has been made to group or cluster the samples into like kinds since our emphasis was on a method to determine empirically the three primary environmental factors for individual sites. Though the vegetation was recorded at each site, no attempt was made to analyse its relationship with the three environmental factors, since it was subject to other influences such as grazing.

Discussion

The study attempted to obtain simple integrative but empirically determinable measures for each of the three main environmental factors of temperature, moisture and soil fertility. The results have been both encouraging and disappointing.

The method of measuring mean temperature was encouraging in terms of the relative ease of making an empirical determination, and its unambiguity and universality in interpretation. The particular approach used in this study of having fixed access holes and a single portable thermometer is cheap to operate, and gives confidence in comparing sites. However, it is realised that mean annual temperature as an explanatory variable does not include the effects of temporal variability on the biological response. Day-degree accumulation, for instance, can include the concept of threshold temperatures appropriate to many organisms, but not that of an optimum and subsequent depression of the response at higher temperatures. Temperature response curves have been established for some species, but probably not for a

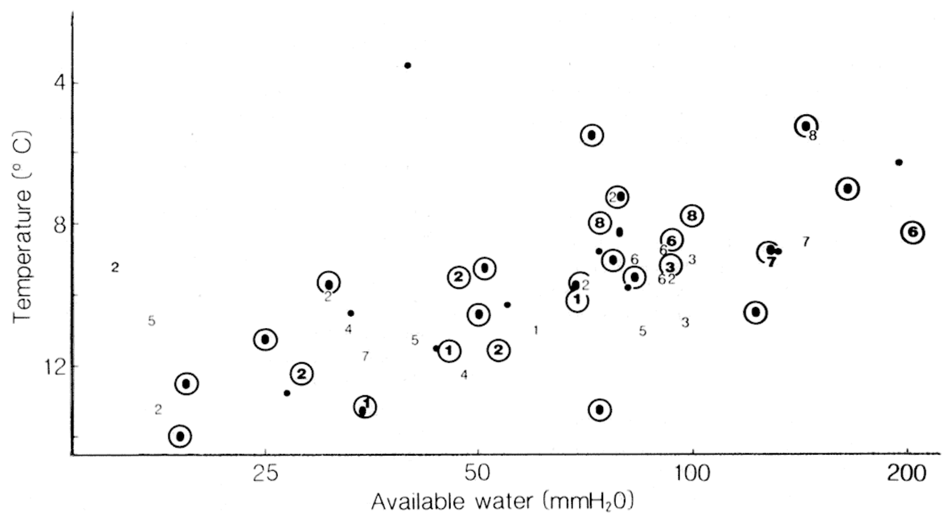

Figure 2: *Distribution of* 63 *sites in the South Island, New Zealand, in relation to mean annual temperature (°C), mean annual available soil water (mm water), and soil fertility (those with an index greater than 400/0 are in bold and ringed). Soils mapped as common to three or more sites have been given a number: 1 = Grampians, 2 = Omarama, 3 = Pukaki, 4 = Mackenzie, 5 = Acheron, 6 = Tekapo, 7 = Craigieburn and 8 = Kaikoura (New Zealand Soil Bureau. 1968).*

sufficient number to determine if a generalised curve could be used to transform data and obtain a more realistic temperature related factor.

The method of determining soil moisture status, from measurement of available water at the same four times during the year as temperature had both good and bad features. The positive features are that soil moisture, like temperature, has large annual cycles, approximated by cosine curves which can be estimated by the empirical measurements made four times a year. The values can be determined on many sites within a short period, with the values related to the moisture levels available to plants, and it did give discrimination between sites. The negative features were that undoubtedly the soil moisture characteristics of a site would be improved by greater frequency of sampling. In practice there has to be a trade-off between the desire to compare a large number of sites and the effort that can be devoted to particular parameters. The sampling of available moisture to a depth of 0.5 m partly compensates for the low frequency of sampling and also limits the effect of minor rain showers during the sampling period. The difficulty of achieving good estimates and reliability in any short term, direct measurements of soil moisture re-focuses attention on the probable integrative properties of soil profile characteristics, as a measure of average soil moisture status over long periods. Many of the world's soil classsification systems use soil moisture as a criteria for subdivision. The limitation of using these as a soil moisture co-ordinate is that they are ordinal, with generally only a discrimination of about 1 in 5-10 within a particular country. It would be desirable to have a quantitatively continuous variable, able to discriminate to at least 1 in 50 within a particular country and 1 in 10 within a region. Hence our suggestion to use empirical measurements of available water.

Soil fertility continues to be the most difficult co-ordinate to quantify because of the complex chemical and biological interactions involved. An analysis using single soil chemical factors had little explanatory power in predicting plant growth in this and another study (Scott and Groves, 1982). Our proposal to define the soil fertility factor by measuring the growth of a test species on soils when they are collected into a common environment still seems to be conceptually useful but has large uncertainties as an empirical quantitative method. The difficulty is in the large residual differences between the soils in terms of plant yields, even when given non-limiting nutrients and a common temperature and moisture environment. It would seem desirable to limit the 'fertility' concept to consideration of nutrient availability (and hence ratio of unamended to nutrient amended plant yields for individual soils), and keep consideration of other soil effects such as texture as a separate issue still not adequately accommodated in the approach suggested.

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