LONGEVITY OF RESPONSE IN PINUS RADIATA FOLIAR CONCENTRATIONS TO NITROGEN, PHOSPHORUS, AND BORON FERTILISERS

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ABSTRACT

In the winter of 1972, a fertiliser trial was established in recently thinned (740 stems/ha) 4- to 5-year-old **Pinus radiata** D. Don regeneration in Harakeke Forest, Waimea County. In a factorial design experiment, nitrogen, phosphorus, and boron were variously applied as urea (168 kg N/ha), superphosphate (112 kg P/ha), and "fertiliser borate 65" (22 kg B/ha). Foliage samples were collected at monthly intervals for the first 3 years, and then about quarterly for 2 more years. Soil samples (0–10 cm) were collected at quarterly intervals and analysed for total nitrogen, Bray-2 phosphorus, Olsen phosphorus, and hot-water-soluble boron.

The concentration of all three nutrients in foliage increased steeply within a few weeks of application, reached a peak in the spring, and declined during the summer. Phosphorus levels then stabilised and remained consistently higher than in the controls for at least 5 years. Nitrogen and boron continued to decline, though at different rates; for nitrogen, the response lasted about 11 months, and for boron about 5 years. Increased levels of extractable phosphorus and boron persisted in the soil for the duration of the trial but appeared to be declining. The applied nitrogen had no obvious effect on soil total-nitrogen status. Tree growth data suggest (1) a positive effect of phosphorus on basal area increment lasting the full 5 years, (2) an effect of nitrogen on diameter increment lasting 1 year, and (3) no effect of boron.

INTRODUCTION

Pinus radiata plantations in the Nelson Province make up about one-tenth of the area of exotic forest in New Zealand. A substantial proportion of these plantations is concentrated in the Waimea County on soils developed on the Moutere gravels – extensive deposits of deeply weathered sands and gravels dating from the Great Ice Age (Pleistocene). *Pinus radiata* forests growing on these soils are commonly affected by deficiencies of one or more nutrients – notably nitrogen, phosphorus, and boron (Will 1978) – and consequently may require remedial fertiliser applications.

In reviewing the progress made with fertiliser trials in established stands of *P. radiata* in the Nelson district, Mead & Gadgil (1978) noted that the addition of nitrogen and phosphorus on the Mapua hill soils, the most infertile of the series formed from Moutere gravels, had produced economically worthwhile results. They also noted that whereas foliar nitrogen levels were increased by nitrogen application for two growing seasons, foliar phosphorus levels were elevated by superphosphate for appreciably longer. On this basis they suggested that nitrogen should be applied on a 3- to 5-year cycle, particularly while the crowns have room to expand. The current practice of prescribing phosphate dressings to maintain foliar phosphorus levels above 0.12% has been a convenient management technique to maintain acceptable tree growth. Foliage analyses are also used to decide which forest areas should be topdressed with boron; a level of 9–12 ppm is considered marginal in dry regions (Mead & Gadgil 1978).

The exploratory trial described here was established to obtain more detailed information on the duration of foliar (concentration) responses to broadcast fertiliser nitrogen, phosphorus, and boron when applied to a young stand of *P. radiata on* Mapua hill soil. At the same time the persistence of applied nitrogen, phosphorus, and boron in the surface soil was examined using routine soil chemical tests.

EXPERIMENTAL

Location

The trial was established in Harakeke Forest in Waimea County, on gently sloping ground (*c.* 7°) with a northerly aspect. The site (41° 13.4′ S, 173° 01.8′ E; 91 m.a.s.l.) was first planted with *P. radiata* in 1931 and this crop was felled in 1967. The dense natural regeneration which followed was thinned to 740 stems/ha in January 1972, i.e., about 6 months before the trial was established.

The soil type in this area, Mapua hill soil (New Zealand Soil Bureau 1968, Ref. No. 32), is a strongly acid, leached soil of very low natural fertility (Chittenden *et al.* 1966) (Table 1). It has developed on weathered greywacke loess and conglomerates, and is one of a sequence formed on deposits of deeply weathered sands and gravels (Moutere Gravel Formation – Rigg 1952). The topsoil consists of a thin, dark grey, weakly structured, sandy loam, and the subsoil a strongly mottled clay loam with coarse prismatic structure. As the clay subsoil has good moisture-holding capacity, deep-rooting crops on this soil type are much less affected by periods of drought than those on other soils in the district (Chittenden *et al.* 1965).

Waimea County is renowned for its sunshine (average annual duration 2407 h, recorded at Nelson Airport) and calm weather (average annual wind run 179 km), being protected from east, west, and south by mountain ranges. Average annual rainfall at Harakeke is 1131 mm. Winter and autumn tend on average to be wetter than summer and spring. The mean annual maximum and minimum temperatures recorded for the nearest climatological station (Riwaka, Motueka) are 29.1°C and –3.4°C respectively.

TABLE 1—Chemical and physical properties of a composite pretreatment soil sample

Depth (cm)	0–15
L.O.I. (%)	4.33
Stones > 2 mm (%)	2.7
Sand (%)	60.5
Silt (%)	20.7
Clay (%)	18.8
pH	4.8
Total N (%)	0.07
Bray-2 P (ppm)	3.8
Olsen P (ppm)	3.4
P retention (%)	26.0
Exchangeable K (me/100 g)	0.12
Exchangeable Ca (me/100 g)	0.7
Exchangeable Mg (me/100 g)	0.45
CEC (me/100 g)	10.5
Hot-water-soluble B (ppm)	0.28

Design, Treatments and Layout

The main experiment was of a completely randomised 2^3 factorial design with treatments, replication, and fertiliser rates as shown in Tables 2 and 3. Supplementary treatments were included to test the effect of delayed applications of nitrogen at full and one-third of the main nitrogen-treatment rate respectively. The original intention for the latter supplementary treatment was to supply the equivalent of a full nitrogen dose (N_1), but to split this into three consecutive annual dressings with the first applied 1 year after the P_1B_1 treatment. Unfortunately the second and third split dressings were not applied and so the plot received only one-third of the full nitrogen dose. As the trial was exploratory in nature and needed to be kept to a small scale, only very limited replication could be considered.

TABLE 2—Treatments and symbols

Treatment	Replication	Treatment symbol
Factorial		
1. $N_0P_0B_0$	2	O
2. $N_1P_0B_0$	1	N
3. $N_1P_1B_0$	1	NP
4. $N_1P_1B_1$	1	NPB
5. $N_1P_0B_1$	1	NB
6. $N_0P_1B_0$	2	P
7. $N_0P_1B_1$	2	PB
8. $N_0P_0B_1$	2	B
Supplementary ("delayed" N treatments)		
9. $P_1B_1 + N_1$ 1 yr later	1	PB,N
10. $P_1B_1 + N_{0.33}$ 1 yr later	1	PB,$N_{0 \cdot 33}$

TABLE 3—Fertilisers and application rates

Level	Elemental rate (kg/ha)	Fertiliser	Fertiliser rate (kg/ha)
N_1	168	Urea	365
P_1	112	Superphosphate	1250
B_1	22	"Fertiliser borate 65"*	112
$N_{0.33}$	56	Urea	122

* A fused ore concentrate consisting essentially of crude anhydrous sodium tetraborate ($Na_2B_40_7$) and containing 20.3% B. This product, which is now marketed under the trade name "Dehybor", is not as readily soluble as borax.

Assuming a soil bulk density of 1.3 g/cm^3, the applied fertilisers could be expected to increase total nutrient element concentrations in the 0–15 cm layer initially by about 86 μg N/g (0.0086%), 57 μg P/g, and 11 μg B/g. These estimates make no allowance for either uneven distribution or rapid movement out of the surface soil, e.g., by leaching, volatilisation, or plant uptake. Considered in relation to pretreatment soil levels of total nitrogen, Olsen and Bray-2 phosphorus, and hot-water-soluble boron (Table 1), such increases, could be expected to have (1) little or possibly no significant effect on total nitrogen, and (2) some measurable effect, intially at least, on extractable phosphorus and boron in the 0–15 cm soil layer.

The trial was laid out in winter 1972 with 14 parallel rectangular plots of 0.0135 ha, each containing 10 trees more or less in a single line at spacings of about 3.0 to 3.7 m. An untreated buffer (6–7 m wide) also stocked with trees was left between each plot. The understorey in each plot was cleared by slasher and removed.

All fertilisers, except the urea for the "delayed" nitrogen treatments, were applied by hand on 6 July 1972 by broadcasting as evenly as possible over the plot area to be treated. Urea was applied to the delayed nitrogen treatment plots on 20 September 1973 after soil and foliage samples had been collected.

Sampling

Soil: Three weeks before treatment, 15 cores (0–15 cm) were taken randomly from the trial area with a Höffer tube sampler (diameter 2 cm); these were bulked and thoroughly mixed to give one composite sample. Subsequent to treatment, similar composite samples were collected from each plot at about quarterly intervals. Samples from replicate plots were bulked by treatment.

Foliage: Samples consisted of needles which had most recently attained mature length and which were growing on second-order branches in the upper (sunlit) third of the tree crown. Depending on seasonal growth and the need to avoid excessive defoliation, between 6 and 10 trees in each plot were sampled. Needles collected from replicate plots were bulked by treatment to reduce sample numbers. Sampling was carried out at monthly intervals from June 1972 to December 1974 inclusive, and thereafter at about quarterly intervals.

Methods of Chemical Analysis

Details of the procedures used, other than that for hot-water-soluble boron, are given by Nicholson (in press). For hot-water-soluble boron, boiling water was added quickly to soil in a 1 : 2 v/w ratio and the suspension immediately shaken for 10 minutes. The suspension was then centrifuged and boron was determined in the supernatant by a manual colorimetric procedure using carmine and sulphuric acid (Hatcher & Wilcox 1950).

Evaluation of Foliar Data

Interaction effects: As not all plots were replicated, and as foliage samples from those plots which were replicated were bulked in the field, a formal analysis of variance normally appropriate to a factorial experiment was not feasible. Consequently the significance or otherwise of interactions could not be statisically evaluated. However, the foliar concentrations for each analogous treatment pair (i.e., treatment combinations inclusive and exclusive of the nutrient under scrutiny but otherwise identical) were plotted together against sampling date to enable a tentative comparison of response patterns to be made. Also, for each pair, foliar concentrations expressed as differences from control were plotted against time to expose any consistent depressive effects of treatment.

Time series graphs were also drawn comparing foliar levels for control and selected treatments to show what effect, if any, particular nutrient treatments had on the foliar status for a nutrient not supplied by the treatment, i.e., where dependence was entirely on the natural soil supply.

Main effects: Each of the applied nutrients nitrogen, phosphorus, and boron was considered in turn as follows:

(a) The concentration differences (D) between the four analogous treatment pairs (which differed only in the omission or inclusion of the nutrient under scrutiny) were first calculated to give four values ($D_1 \ldots D_4$) per sampling date.

(b) The mean difference ($\bar{D}$) at a particular date, given by $\sum_{i=1}^{4} D_i/4$, was then plotted against years from treatment date to provide a time series in which the mean response pattern for foliar concentration was represented as difference from zero.

(c) Where $\bar{D}$ appeared to decline exponentially with time, a decay law curve was fitted to the relevant data using the general equation:

$$y = ae^{-bx}$$

in which y = mean foliar concentration difference ($\bar{D}$) at a particular date

and x = time in decimal years from the start of 1973.

For foliar nitrogen, the least squares fit of data points for consecutive foliage samples of the fifth to nineteenth collections inclusive was calculated, and for foliar boron the fit for those relating to the eighth to fortieth collections inclusive was found.

(d) A one-tailed 't' test was used to calculate the 95% confidence limit at which $\bar{D}$ ceased to be significantly greater than zero. Firstly, the concentration differences $D_1 \ldots D_4$) found for each analogous pair over a particular sequence of sampling dates were averaged to give means ($\bar{D}_1 \ldots \bar{D}_4$). In order to obtain a confidence limit free from influence by $\bar{D}$ values much greater than 0, an appropriate sequence of observations was used to calculate the standard from the means ($\bar{D}_1 \ldots \bar{D}_4$).

(e) The intercept of the decay curve and 95% confidence for difference from zero was used to estimate the duration of significant foliar response to the applied nutrient.

Evaluation of Soil Test Data

Where concentrations of a particular nutrient in the soil were increased by treatments supplying that nutrient, the sets of values for treatments which respectively included and excluded the relevant nutrient were pooled for each sampling date and averaged. These means were then plotted against sampling date to show the trend with time. As for foliar data, the mean difference ($\bar{D}$) in soil concentration at a particular date was plotted against sampling date to provide a time series. The 95% confidence limit at which $\bar{D}$ ceased to be significantly greater than zero was found by means of a one-tailed 't' test. The estimated standard error term used in this test was derived from data for the final 10 soil samples collected, i.e., when the values of phosphorus and boron were most closely approaching background level.

Growth Measurements and Treatment of Data

Individual tree heights and diameter at breast height over bark (d.b.h.o.b.) were measured on 21 June 1972, i.e., about 3 weeks prior to treatment, and again on 16 August 1977 on termination of the trial. An additional measurement of d.b.h.o.b. was made 1 year after treatment, on 1 August 1973. Basal areas (m^2/ha) were calculated from the diameters of the 10 trees in each plot and plot size of 0.0135 ha.

Sectional measurements of sample trees were used to estimate tree volumes. In 1972, 10 trees representative of the stand diameter range were measured. In 1977, five trees from each plot were measured (usually all in the same half of the plot unless any individuals were obviously unrepresentative). Volumes were calculated from the sectional data using the method described by Whyte (1971).

RESULTS AND DISCUSSION

Nutrient Concentrations in Foliage

Foliar values currently used to assess the nutrient status of *P. radiata* in New Zealand forests have been listed by Will (1978). The recommended sampling period for diagnostic purposes is mid to late summer. Considered in relation to Will's criteria, the March foliar nitrogen concentrations in control trees (Fig. 1) rate marginal (i.e., inside the 1.2–1.5% range) for the first 3 years of the trial and low ($< 1.2\%$) for the

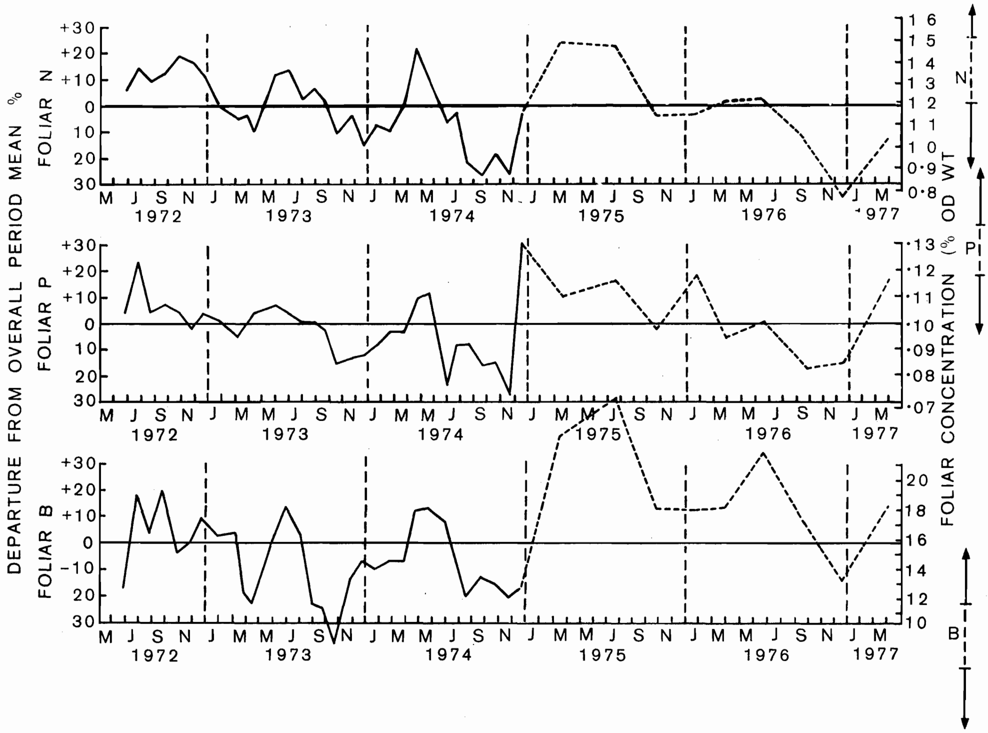


FIG. 1—Time series graphs comparing percentage departure from the over-all mean for foliar nitrogen, phosphorus, and boron in control trees for the whole trial period. The period of intensive sampling is indicated by the solid line and the less intensive period by the hatched line. Ratings for summer foliar nitrogen, phosphorus, and boron values are shown by the bar in the right-hand margins: arrow up = satisfactory range; arrow down = low range; hatched span between = marginal.

final 2 years. The March foliar phosphorus values consistently rate low (< 0.12%) while the foliar boron consistently rate satisfactory (> 12 ppm) in the 5 years of the trial.

The less-than-satisfactory ratings for nitrogen and phosphorus accord with the results of past studies in the trial area (Adams & Walker 1975; Mead & Gadgil 1978), which have generally indicated that pine growth on Mapua hill soil is limited by deficiencies of these nutrients.

Samples representing the 10 treatments at a single date (17 December 1976) were analysed for potassium, calcium, and magnesium as well as nitrogen, phosphorus, and boron; the resultant mean concentrations (percentage oven-dry weight) and standard deviations were 1.45 ± 0.22 for potassium, 0.18 ± 0.04 for calcium, and 0.088 ± 0.013 for magnesium. Although the sampling date is outside the recommended (standard) sampling period, these levels suggest adequate potassium and calcium but possibly marginal magnesium supply.

Foliar Concentration Response to Applied Nitrogen

(i) *Full rate (168 kg N/ha) applied July 1972*

Figure 2A shows (1) a steep increase in $\bar{D}_N$ over the first 4 months after treatment, leading to a peak in October (spring); (2) a rapid decline over the next 2 months (late spring); and then (3) a progressively slower rate of decline until $\bar{D}_N$ closely approached zero about a year after treatment. The exponential decay curve fitted to the $\bar{D}_N$ data for the period October 1972–December 1973 intercepts the confidence limit for least significant difference from zero ($p < 0.05$) at 10.6 months from date of original treatment. The half life for $\bar{D}_N$ on the fitted decay curve is 0.144 years (53 days). The response in foliar nitrogen concentration to the applied nitrogen was shortlived, lasting barely a year. Miller *et al.* (1976) and Miller (1979) suggested that duration of tree growth responses to applied nitrogen may depend very largely on the amount of nitrogen accumulated within the trees soon after treatment. In the present trial, the shortlived improvement in foliar nitrogen status suggests that any nitrogen accumulated within the tree during the first few months after fertiliser application was rapidly utilised. Growth dilution, e.g., through crown and root expansion, might account for the reversion to pretreatment foliar nitrogen levels within a year or so of treatment.

(ii) *Full rate (168 kg N/ha) applied in early spring 1973*

The "delayed" nitrogen treatment, applied a little over a year after the main treatments in September, elicited a somewhat different foliar response pattern (Fig. 2B) from that of the mid winter application. A steep increase in foliar nitrogen response (D^*_N)† was recorded within a month of treatment, and then a peak was reached about November. Between December and January a rapid decline was recorded to about half peak height; thereafter, for the remainder of the year, D^*_N remained significantly ($p < 0.05$) greater than zero. However, by the first sampling date in 1975, D^*_N was no longer significantly greater than zero. Thus the available data suggest a foliar response duration of not much more than 1.25 years. Delaying the application may have extended the duration of response by, at best, only 4 months or so. A comparison of the trends shown in Fig. 2A and 2B suggests that a more favourable pattern of response may have resulted from the delayed treatment. However, as the "delayed" treatment was not replicated, inferences drawn from the foliar data must remain tentative.

Miller (1966) and Humphreys *et al.* (1972) have both reported strong statistical correlation of weather factors with foliar levels. As records show that appreciable differences existed in seasonal rainfall distribution at Harakeke over the period of the trial, it is quite conceivable that climatic factors were at least partly responsible for the differences in response pattern.

(iii) *One-third rate (56 kg N/ha) applied in early spring*

The foliar response (D'_N)† to this treatment (Fig. 2C) was commensurately smaller in magnitude than that to the similarly delayed full rate (cf. Fig. 2B) but similar in

† D^*_N = difference at a date in foliar nitrogen concentration between treatments PB and PB,N.

D'_N = difference at a date in foliar nitrogen concentration between treatments PB and PB,$N_{0\cdot33}$.

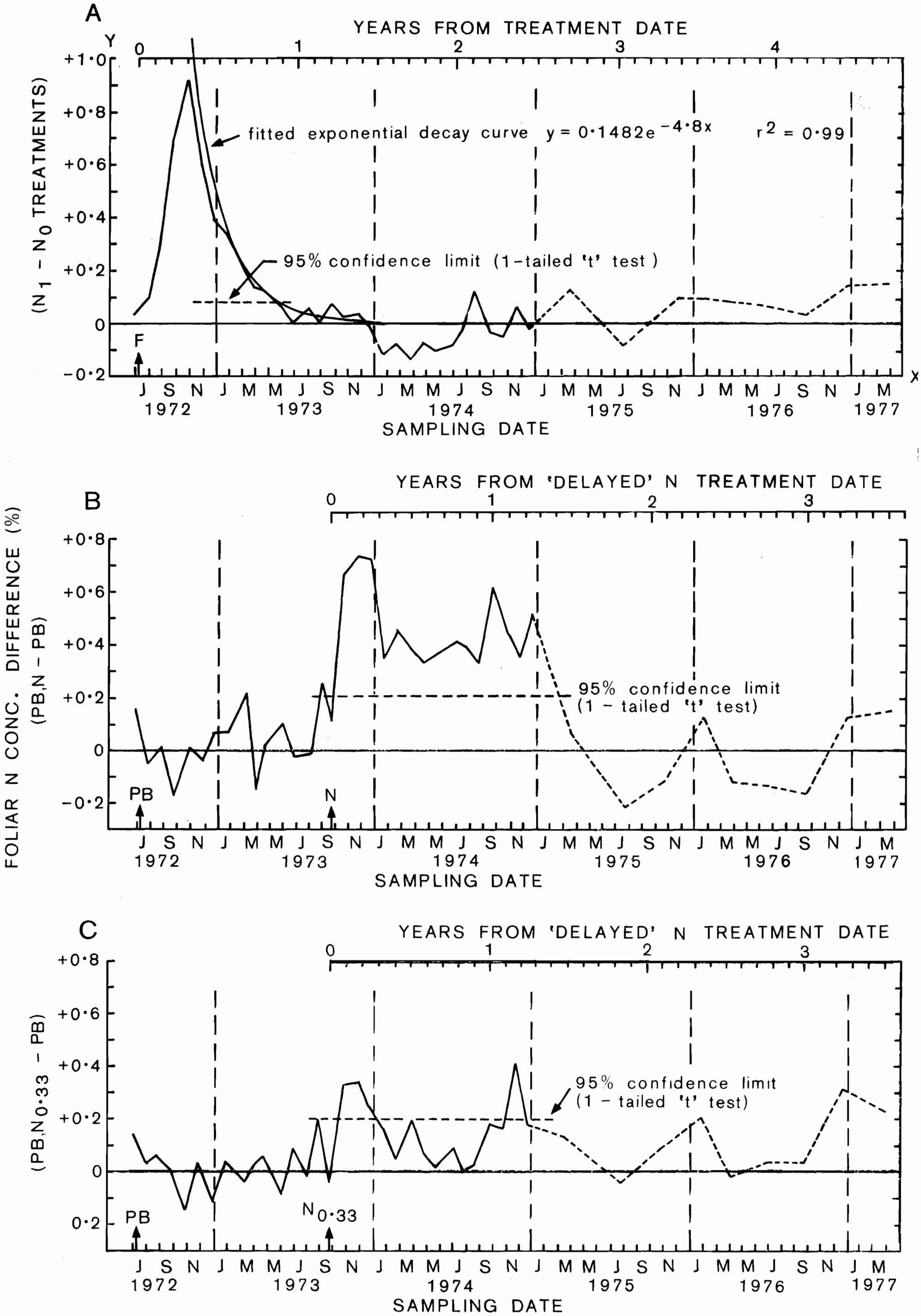


FIG. 2—Time series showing patterns of foliar response to broadcast urea: (A) 365 kg/ha on main treatment date 6 July 1972, (B) 365 kg/ha applied about a year later on 20 September 1973, and (C) 122 kg/ha (one-third of full rate) applied at the same time as (B).

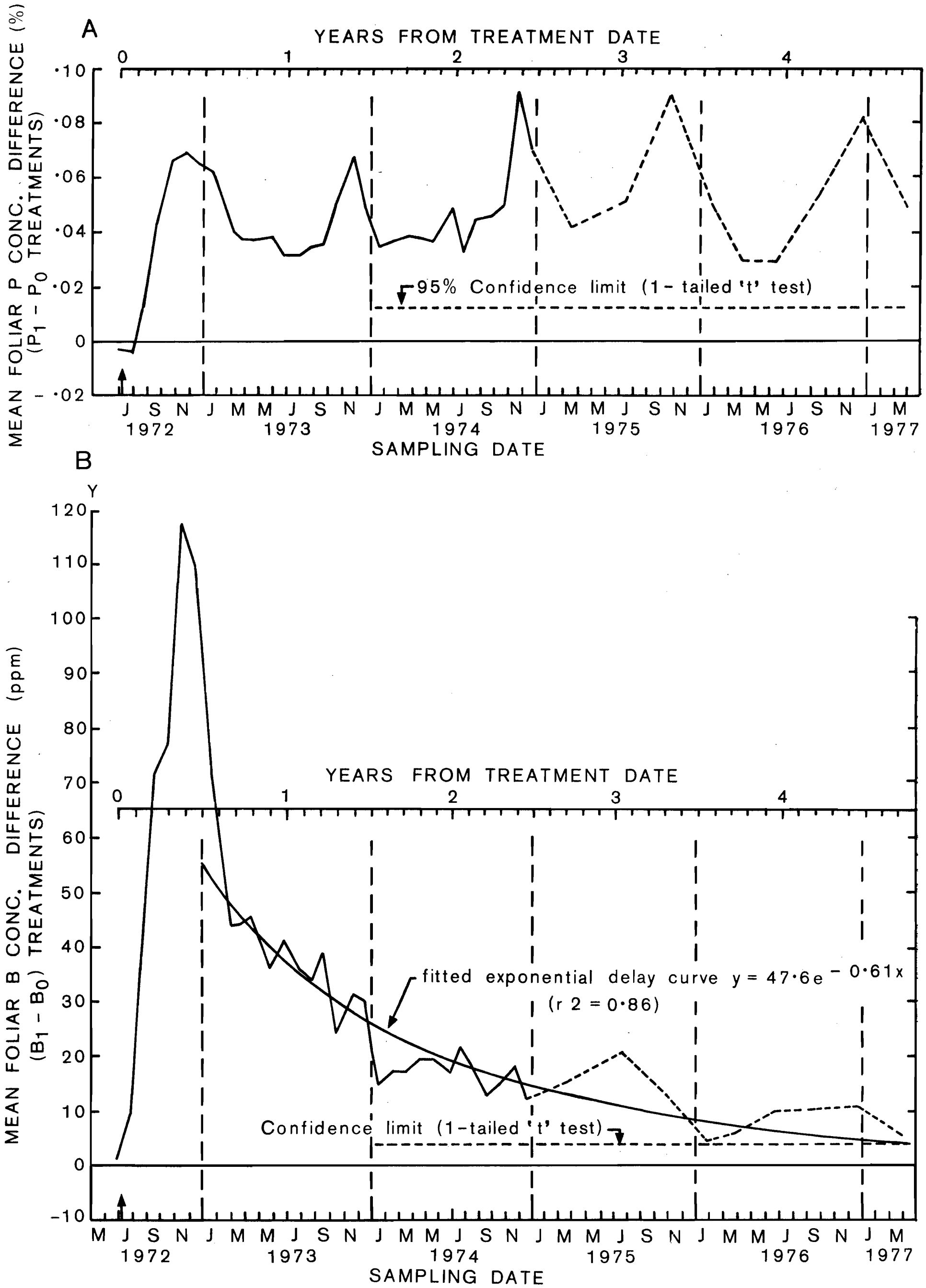


FIG. 3—Time series showing mean pattern of foliar response to broadcast fertilisers: (A) superphosphate (1.25 t/ha), and (B) "fertiliser borate 65" (112 kg/ha).

pattern. The foliar response ceased to be significant ($p < 0.05$) within 4 months of treatment, though a sharp peak recorded in the following spring suggests the actual response duration may in fact have been of the order of 12 months. In the absence of replication, these conclusions must remain tentative.

Foliar Concentration Response to Applied Phosphorus

The superphosphate elicited a strong and enduring foliar phosphorus response ($\bar{D}_P$); $\bar{D}_P$ seems to have been seasonally greatest in spring of each year when prominent peaks were recorded (Fig. 3A). Despite seasonal fluctuations, $\bar{D}_P$ showed little sign of any consistent decline over the trial period. It seems probable, therefore, that the response would have persisted well beyond the 5-year time limit set for the trial.

Many instances of long-term foliar (and tree growth) responses to heavy phosphate dressings have been reported from Australasia for *P. radiata* (e.g., Will 1965; Gentle *et al.* 1965; Ballard 1978; Flinn *et al.* 1979). Mead & Gadgil (1978) have listed the durations of foliar response to various rates of applied phosphorus recorded in *P. radiata* stands of various ages on sites throughout New Zealand. Their data indicate that the duration of response to superphosphate at 1.25 t/ha on Mapua hill soils can last from at least 3 years to more than 5 years.

Foliar Concentration Response to Applied Boron

Pattern and longevity of response

A modest increase in $\bar{D}_B$ had already occurred within 3 weeks of treatment (Fig. 3B) and the increase continued steeply until a peak was reached in November (late spring) about 4 months after treatment. At this time, foliar concentrations for treatments which included boron ranged from 91 to 231 ppm, whereas those where boron was excluded were in the range 17–20 ppm. Over the December–February summer period, $\bar{D}_B$ declined rapidly, but by about March (late summer) the rate of decline had begun to moderate. Thereafter, if relatively minor fluctuations attributable to such sources of variation as season, climate, and sampling error are disregarded, the trend seems to closely follow the exponential decay law. The decay curve fitted to the $\bar{D}_B$ values (Fig. 3B) intercepts the confidence limit ($c = 3.2$ ppm) for least significant ($p < 0.05$) difference from zero at a point about 4.91 years from treatment date. The half life for $\bar{D}_B$ on this curve is 1.14 years. Graphs of foliar data for analogous treatment pairs suggest that the foliar response may in some instances have persisted somewhat beyond the estimated 4.9 years. Soil test data (Fig. 4B) indicate that, at the conclusion of the trial, hot-water-soluble boron levels were still significantly higher ($p < 0.05$) for treatments which included boron than for those which did not.

Potentially toxic boron levels

Pinus radiata is known to be very sensitive to boron supply (Marzo Munoz-Cobo & Marcos de Lanuza 1970). Although there is no record of any symptoms of toxicity having been observed in the present trial, the peak levels recorded (Table 4), particularly for the NB treatment, seem high enough to be considered potentially toxic. Marcos de Lanuza (1966) reported that growth of solution-cultured *P. radiata* seedlings

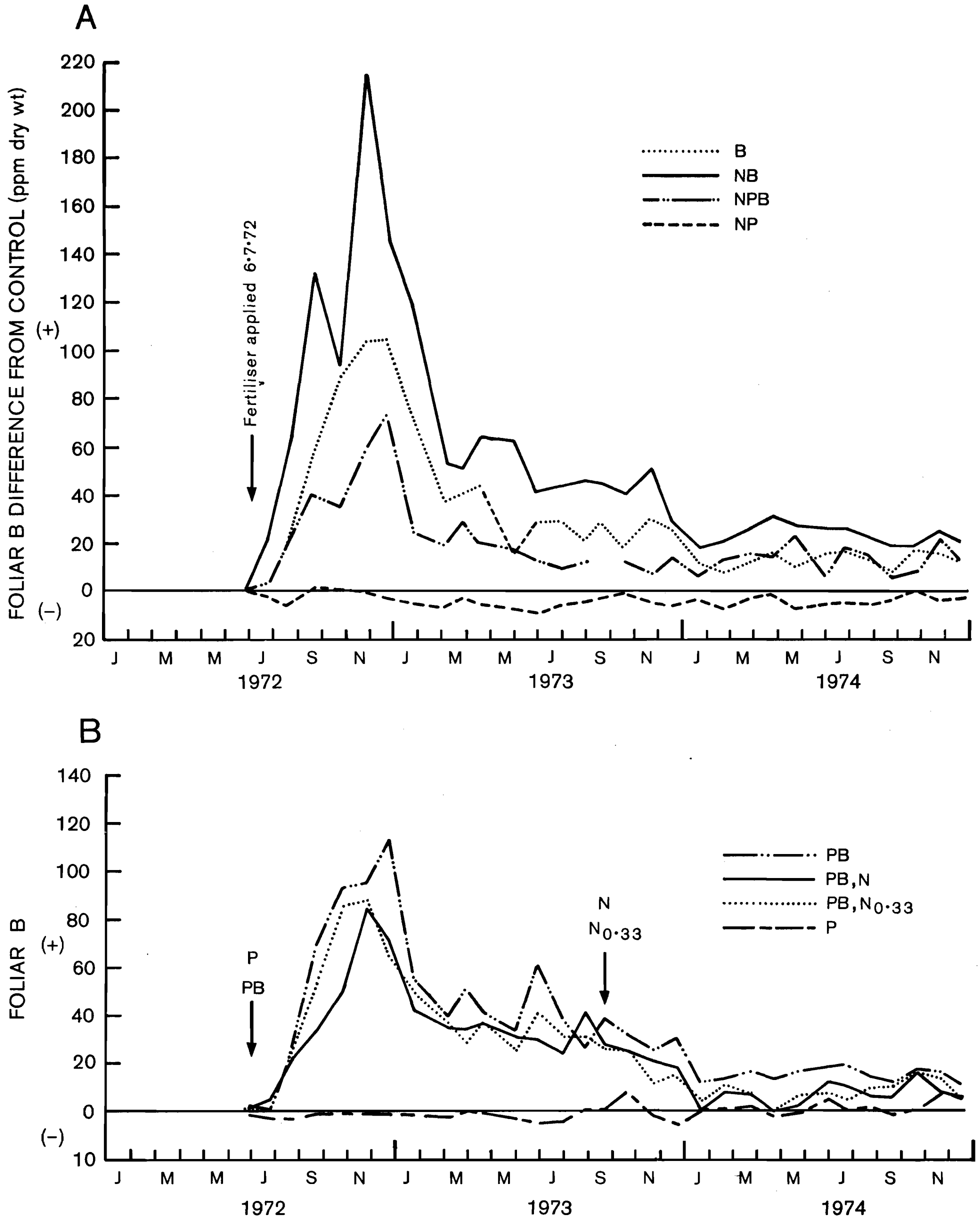


FIG. 4—Time series showing foliar boron difference from control for (A) treatments B, NB, NPB, and NP, and (B) treatments PB, PB,N, PB,$N_{0.33}$, and P.

decreased markedly and toxicity symptoms appeared when foliar boron exceeded 50 ppm. Smidt & Whitton (1975) subsequently reported that toxicity was associated with a level of about 200 ppm B in foliage of mature *P. radiata*, and Mead (1978) reported that slight toxicity (1–2% of needle length affected by necrosis) was associated with 40–58 ppm B in current foliage.

TABLE 4—Summary of peak foliar boron concentrations recorded for the various treatments in the spring following treatment

No boron applied		Boron applied	
Treatment	Foliar B level (ppm)	Treatment	Foliar B level (ppm)
O	19	B	122
N	31	NB	231
NP	21	NPB	91
P	19	PB	130, 102*, 104†

* PB,N

† PB,$N_{0.33}$

Possible nutrient interaction effects

Graphs of foliar data against time for analogous treatment pairs suggest that, with one noteworthy exception, effects which could be attributed to interaction were generally either non-existent or not large enough to be of practical significance. The one notable exception was an apparently large N × B positive interaction. The steep increase in foliar boron concentration which occurred in the spring after application of the borate fertiliser was much greater for the NB treatment than for all other boron treatments (Fig. 4). This suggests that, where nitrogen and boron were applied together but without phosphorus, the applied nitrogen had an enhancing effect, initially at least, on uptake of applied boron. By contrast, the inclusion of phosphorus as superphosphate in the PB and NPB treatments appears to have a moderating effect on the initial steep increase in foliar boron concentration. Olsen (1972) stated that "plants grow normally only when a certain balance exists in the uptake of Ca and B", and "in soils that contain B in excess of the amount required for optimum growth, toxic effects may be reduced or prevented by adding Ca". Since superphosphate contains about 20% calcium by weight, it may be that this component of the fertiliser actually exerted the moderating effect. A comparison of foliar boron data for the control and the N treatment respectively suggests that the N treatment may have produced a very shortlived improvement in foliar boron status even where boron was not applied.

In the absence of replicated data, the possibility that the greater peak in foliar boron recorded for the NB treatment was due to site variability rather than to an interaction cannot be discounted. The fact that the hot-water-soluble boron values for the NB treatment plot were consistently higher during early months of the trial than those for other boron treatments could indicate greater retention of applied boron than in other boron-treated plots. However, unpublished data from a fertiliser trial in Canterbury, New Zealand (D. J. Mead pers. comm.), also indicate that the foliar boron response to nitrogen + boron treatment is much greater than to nitrogen + phosphorus + boron. As the particular nitrogen + phosphorus + boron treatment in the Canterbury trial also gave a greater growth response than the one without phosphorus, there is some possibility that the lower foliar boron level recorded for the former treatment may have resulted from growth dilution. Since the phosphorus source used did not contain calcium, this nutrient element could not have played any part in moderating the apparent synergistic effect of nitrogen on boron uptake in this instance.

There was no evidence in the time series graphs comparing foliar nitrogen concentrations of no-nitrogen treatments with those of the control, that P, B, or PB treatments resulted in any consistent improvement in foliar nitrogen status. This conflicts with the suggestion of Adams & Walker (1975) that additions of phosphorus might eventually lead to an improvement in the nitrogen balance of the system. The foliar data do indicate that, where nitrogen was applied without phosphorus, there was a distinct improvement in foliar phosphorus status the following spring. The improvement was apparently shortlived as, in subsequent seasons, foliar phosphorus levels were as low as or lower than control values.

Variation in Late Summer Foliar Levels

In New Zealand, late January to the end of March is the sampling period advocated by Mead & Will (1976) as a suitable compromise where routine analysis of *P. radiata* foliage for a range of nutrients, rather than a single element, is intended. As foliage samples were collected only quarterly during the latter part of this trial, the March data corresponding to the standardised period are used here (Fig. 5) to provide an indication of year-to-year variation in foliar levels. These graphs show that when dependence for a particular nutrient is entirely on natural supply, year-to-year variation in foliar status of that nutrient can be quite large. This accords with Humphreys *et al.* (1972) who reported that various climatic factors contributed significantly to annual variation in foliar levels of particular nutrients. It seems likely, therefore, that such factors as variation in seasonal rainfall distribution contributed in some measure to the annual variation in March foliar values recorded in this study. Sampling error (due to different collectors and different trees sampled), analytical error, and changes in site occupation by the growing trees (confounded in this study) must also be components of the variance recorded.

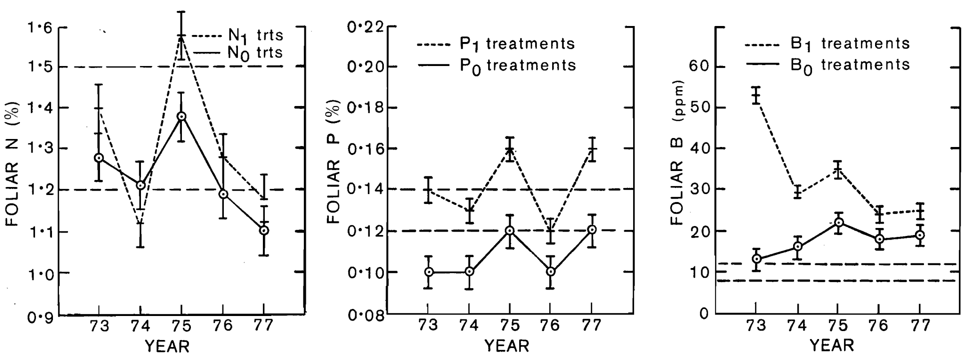


FIG. 5—Annual variations in March foliar levels of nitrogen, phosphorus, and boron. Points joined by solid line are mean values for treatments which excluded the particular nutrient being considered, while those joined by a broken line are means for treatments which included it. The vertical bars represent estimated standard error of the mean.

The time series for the March foliar data (Fig. 5) suggest that, in the absence of applied phosphorus and boron respectively, there has been no consistent decline in foliar phosphorus and boron status with the passage of time. If anything, the over-all trends suggest a slight improvement in boron status; the corresponding series for foliar nitrogen suggest a tendency for its status to decline with time, though 1975 was exceptional. The 1975 March levels of nitrogen, phosphorus, and boron for treatments which excluded the relevant applied nutrient were higher than in the years before and after, possibly as a result of the much wetter-than-usual summer period.

Long-term Effects of Treatments on Selected Soil Chemical Properties

Total nitrogen

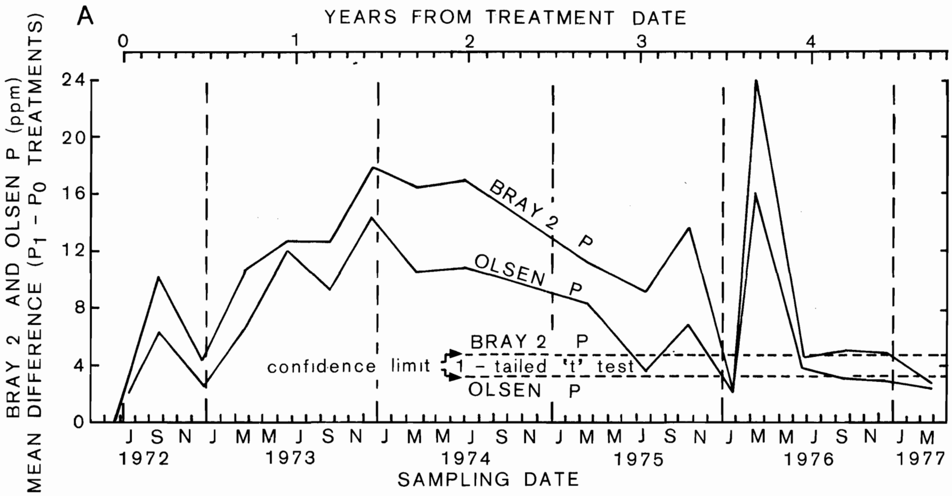
Total nitrogen values for the trial period did not show any consistent increase in nitrogen concentration in the surface mineral soil at any stage after application of urea. The apparent lack of sensitivity of total nitrogen for detecting changes in soil nitrogen status is attributed to (1) the disproportionately large "background" level of soil nitrogen relative to the amount of fertiliser nitrogen added, (2) small-scale heterogeneity within plots for total nitrogen, and perhaps (3) rapid movement of the applied nitrogen from the forest floor (*see* Cole & Gessel 1965).

Bray-2 and Olsen phosphorus

Differences in extractable phosphorus were readily detected between samples from treatments with and without phosphorus applied, by both Bray-2 (NH_4F-HCl) and Olsen ($NaHCO_3$) tests (Fig. 6A). The Bray-2 extractant is designed to remove easily acid-soluble forms of phosphorus (largely calcium phosphates and a portion of the iron and aluminium phosphates) and has been most successful on acid soils (Olsen & Dean 1965). To a large extent bicarbonate and fluoride appear to remove about the same compounds, although fluoride will react more vigorously and remove phosphate that is not available to bicarbonate ions (Thomas & Peaslee 1973). The Bray-2 extractant consistently extracted more phosphorus than the Olsen. The linear regression relationship between these two sets of test results (167 pairs of values) is given by the equation:

$$\text{Olsen P (ppm)} = 0.191 + 0.664 \text{ Bray-2 P (ppm)} \quad (r^2 = 0.873;\ p < 0.001)$$

The variance among Bray and Olsen test data was generally greater for treatments that included phosphorus than for those that did not. Moreover, as the Olsen and Bray phosphorus trends for the trial period (Fig. 6A) have closely matching patterns, it appears that the greater variance in extractable phosphorus levels for treatments with phosphorus applied is largely attributable to small-scale soil heterogeneity within the treated plots. It seems, therefore, that any initial unevenness in fertiliser spread (perhaps compounded and magnified by understorey effects) persisted for the duration of the trial. This suggests that very little lateral movement of the applied phosphate occurred after application. As a consequence, the sampling intensity was inadequate to establish a firm average trend for extractable phosphorus status. Nevertheless, the data clearly show (Fig. 6A) that significant increases in both Bray-2 and Olsen phosphorus resulted from the application of superphosphate and that the raised levels persisted for at least 4 years. The average trends suggest that extractable phosphorus levels in plots with superphosphate applied may have reached a peak about December 1973, i.e., 18 months after application, and thereafter (apart from occasional apparently erratic fluctuations) tended to decline gradually. The reason for the high values recorded for phosphorus treatments in March 1976 is not clear. By about mid 1976, i.e., about 4 years after fertiliser application, the mean difference from samples from treatments without phosphorus amounted to about 2.4 ppm for both tests. On the final sampling date, about 5 years after fertiliser application, the mean difference, although still positive, was no longer significant.



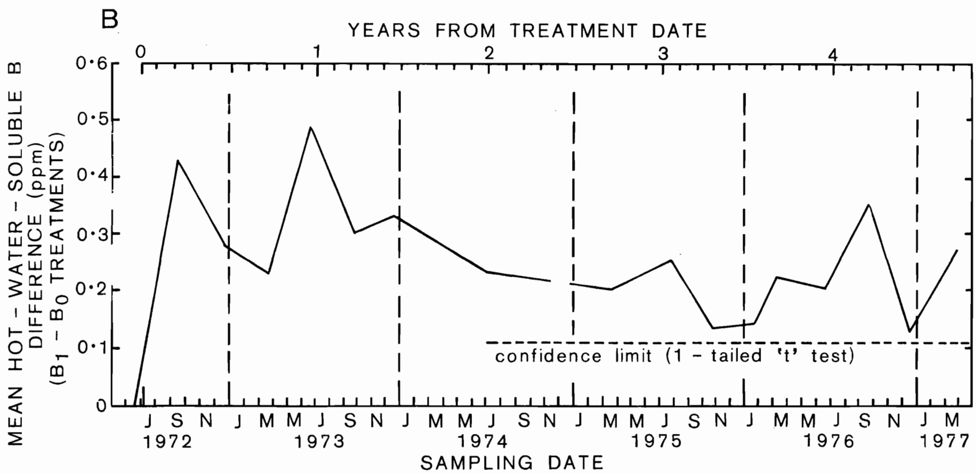


FIG. 6—Time series showing the average trends for (A) Bray-2 and Olsen extractable phosphorus levels, and (B) hot-water-soluble boron levels, where these are expressed as the mean difference between analogous treatment pairs.

Hot-water-soluble boron

Hot-water-soluble boron (HWSB) is generally accepted as the best index of availability of boron for plants (Wear 1965). The persistence of applied boron in soils is determined largely by the soil type and the form of boron applied (Murphy & Walsh 1972); borates leach readily from sandy soils but are much less susceptible to leaching from soils high in silts and clays. The rapid HWSB test used in this trial differs from the conventional reflux extraction method (*see* Experimental) and has not been calibrated in relation to the reflux method. Consequently the results cannot usefully be considered in relation to criteria established for the reflux method.

At the earliest sampling date after treatment, increased HWSB levels were recorded in all plots treated with "fertiliser borate" (Fig. 6B). Despite several apparently erratic fluctuations, the significantly elevated HWSB levels ($p < 0.05$) recorded for treatments which included boron persisted for the duration of the trial, though the trend does suggest a gradual decline with time. As for extractable phosphorus, the fluctuations in HWSB are attributed to small-scale heterogeneity within the plots – probably as a result of initial unevenness in fertiliser spread. Foliar boron concentrations were not found to be significantly correlated with HWSB levels.

Evaluation of Growth Data

Lack of replication and blocking in this exploratory trial largely precluded useful, rigorous, statistical analysis of the growth data. However, the data (Table 5) suggest that:

(1) Applied nitrogen had a positive ($p < 0.05$) effect on diameter increment for the year following treatment only;

(2) Applied phosphorus had a positive, though statistically non-significant, effect on both diameter and basal area increments for the whole trial period;

(3) Applied boron had no obvious effect on the parameters measured.

As other nearby fertiliser trials on the same soil type have clearly demonstrated large growth responses to applied nitrogen and phosphorus (Mead & Gadgil 1978), the response to phosphorus in this trial, which is apparent in the means but not significant at conventional test levels, has strong precedents.

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TABLE 5—Comparison of nutrient main effects on selected growth parameters (unadjusted mean values are shown with mean values adjusted for dummy (positional) covariate in brackets alongside)

Parameter	Nitrogen				Phosphorus				Boron			
	Without		With		Without		With		Without		With	
Height increment 1972–77 (m)	1.06	(1.08)	1.14	(1.10)	1.05	(1.10)	1.12	(1.08)	1.04	(1.08)	1.13	(1.09)
Diameter increment 1972–73 (cm)	2.25	(2.31)	3.16	(3.05)	2.40	(2.53)	2.70	(2.58)	2.61	(2.72)	2.49	(2.38)
Diameter increment 1972–77 (cm)	12.1	(12.4)	12.3	(11.6)	10.8	(11.5)	13.5	(12.8)	11.5	(12.2)	12.8	(12.1)
Basal area increment 1972–77 (m^2/ha)	15.5	(16.0)	17.4	(16.4)	14.0	(15.2)	18.2	(17.0)	15.8	(16.9)	16.4	(15.3)
Final volume 1977 (m^3)	0.66	(0.69)	0.72	(0.66)	0.64	(0.70)	0.72	(0.66)	0.64	(0.70)	0.72	(0.66)

The underlined pair differ significantly ($p \leq 0.05$)

Note As the dummy covariate generally reduced the residual mean square in covariance analyses and was significant, or close to it, the adjusted values probably give a fairer indication of differences. The dearth of statistically significant nutrient effects is hardly surprising in view of the paucity of degrees of freedom for residual in the covariance analyses.

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