LONG-TERM FOLIAR PHOSPHORUS RESPONSE OF PINUS RADIATA TO SUPERPHOSPHATE FERTILISER

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ABSTRACT

Foliar phosphorus concentrations have been recorded for up to 15 years in the seven blocks of a long-term trial monitoring phosphorus fertiliser application rates on **Pinus radiata** D. Don. In unfertilised plots on the most deficient sites foliar phosphorus concentrations have not altered greatly from 0.06% P (o.d. wt) over time, but at the less deficient sites foliar phosphorus has tended to decline over time. In fertilised plots there was an immediate increase in foliar phosphorus, proportional to the amount of fertiliser applied, followed by a slow decline over time. After thinning there tended to be a rise in foliar phosphorus lasting for about 2 years. A simple multiple regression model explained 73% of the total variation. Further variation in foliar phosphorus associated with annual fluctuations accounted for only 5% of the total.

Keywords: phosphorus; superphosphate; foliar nutrients; foliage sampling.

INTRODUCTION

The effect of phosphorus fertiliser application to *Pinus radiata* forests in New Zealand is monitored by regular foliage sampling. Sometimes the results of this monitoring are surprising and irrational. For example, areas recently fertilised occasionally appear to be still deficient in foliar phosphorus. There are several possible causes for such a finding, including uneven fertiliser spreading, poor sampling of foliage, and a large inherent variation in foliage sampling itself. In the context of the management operation it is not possible to resolve this issue. However, we have been monitoring foliar phosphorus in a long-term phosphorus rates trial series for 15 years and these data provide us with an opportunity to describe the pattern of variation of foliar phosphorus in research plots and thereby exclude some possible causes of the variation in the management system.

METHODS

The Trial

The trial has been fully described by Hunter & Graham (1982). There are seven blocks distributed in four forests in the Auckland region – three in Whangapoua Forest in the Coromandel area, two in Riverhead Forest just north of Auckland, one in Maramarua Forest south of Auckland, and one in Glenbervie Forest near Whangarei. All the blocks are on clay soils of medium phosphorus-retention and low in available-phosphorus.

Two of the three blocks in Whangapoua were established in 1967, the other in 1969. Glenbervie was established in 1970, Maramarua in 1971, and the two blocks at Riverhead in 1973.

Nine combinations of fertiliser treatment were used in all; however, only six are common to all blocks. There was a control (no fertiliser), superphosphate at 625 kg/ha, 1250 kg/ha, and 2500 kg/ha, and repeat applications of both 625 kg/ha and 1250 kg/ha at fixed intervals or at intervals determined by foliar phosphorus (Table 1).

TABLE 1—Superphosphate fertiliser treatments (kg/ha)

	Found in blocks
Control - no fertiliser	All
625 at trial establishment	All
1250 at trial establishment	All
2500 at trial establishment	4–7
625 at trial establishment and again after 10 years	All
625 at trial establishment and again after 5, 10, and 15 years	All
625 delayed to 5 years after trial establishment	All
625 repeated whenever foliar P fell below 0.12% or was between 0.12% and 0.13% for two consecutive years	3–7
1250 with the same foliar-P-triggered repeat procedure	6–7

Climate

From 1947 to 1980 Glenbervie Forest had an average annual rainfall of 1934 mm with an extreme low of 1438 mm, and an average annual temperature of 13.7°C; Riverhead 1432 mm (1085 mm) and 13.7°C; Whangapoua 1873 mm (1436 mm) and 14.6°C; Maramarua 1263 mm (902 mm) and 13.6°C (New Zealand Meteorological Service 1983). With average daily and yearly ranges in temperature of around 10°C the climate at all four forests can be described as mild, equable, and moist.

Field Collection of Foliage

Throughout the study foliage was collected from the recently matured needles on secondary branchlets in the upper third of the crown of seven trees per plot. Until 1978 the foliage from each tree was kept separate. After 1978 one composite sample was taken per plot. Initially foliage collection was combined with plot remeasurement and varied between June and November, with most collections occurring in the main winter months. In 1976 Mead & Will published the results of a study in seasonal variation of nutrient content for which the field work had been done in 1966. They concluded that summer-autumn sampling would give more stable results. This conclusion affected their research work even prior to the appearance of the paper for, in 1974 and subsequently, foliage collection was made between February and March.

The unfertilised plots and some of the repeat-fertilised plots have been sampled annually. Other plots have been sampled on a 2- to 3-year cycle.

Laboratory Procedure

Foliage was dried to constant weight at 70°C and ground. Up to 1978 it was then dry ashed and digested with hydrochloric acid. After 1978 the ground samples were digested using sulphuric acid and hydrogen peroxide in the presence of lithium sulphate. In both digests the phosphorus concentration was determined using the vanadomolybdate yellow method (Nicholson 1984).

Forty percent of the samples were collected prior to 1974, i.e., in the winter. Sixty percent were collected before the change of laboratory method.

Data Analysis

For those years (1967–78) for which sample trees were individually chemically analysed, plot average phosphorus concentration was calculated. All the plot means were tabulated and studied. The main effects were studied by graphing the data. Most of the main effects chosen were those apparent from the semi-orthogonal trial design, e.g., rate and timing of fertiliser application and time since the fertiliser was applied. Several of these factors seemed to have a very strong effect on foliar phosphorus response. A series of simple regression models was therefore built using the statistical package GENSTAT (1983). The final model selected was chosen for its simplicity and high proportion of variance explained. The authors expressly rejected the strategy of hunting through a pool of variables for a model, however complex, that was distinguished simply by its goodness of fit. Such a model, because of the degree of internal confounding of some of these data, could be very untrustworthy.

RESULTS

Control plots with very low initial foliar phosphorus have maintained relatively uniform low levels of phosphorus with time (Fig. 1). Plots with higher initial phosphorus concentrations have shown some decline with time.

Figure 2 shows foliar phosphorus concentrations in three of the plots fertilised with 1250 kg superphosphate/ha at plot establishment. In the interests of clarity only three plots can be shown. However, the response trend in these plots is typical for this treatment. After fertiliser application there was an abrupt rise in foliar phosphorus. The size of the rise seems to be independent of the degree of deficiency at time of application. Some year-to-year variation is apparent but the over-all trend in foliar phosphorus is a decrease with time.

From the data it appeared that there was a rise in foliar phosphorus (independent of fertiliser application) associated with thinning (Fig. 1 and 2). In six of the seven unfertilised plots there is a weak trend for foliar phosphorus to increase after thinning. In three out of the four instances shown in Fig. 2 and in the majority of the other fertilised plots, however, there was a marked rise in foliar phosphorus within 2 years of thinning.

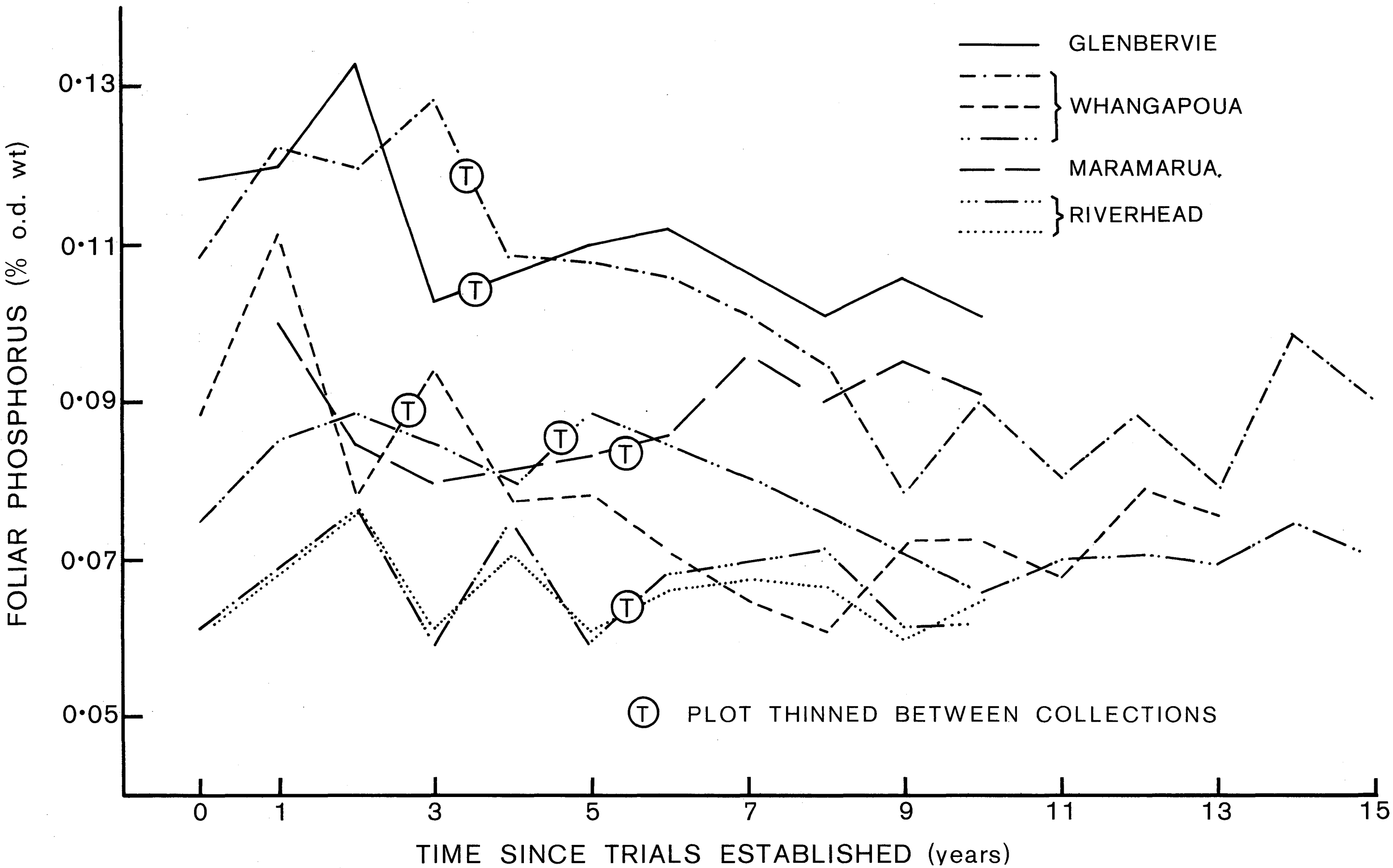

FIG. 1—Foliar phosphorus concentration in seven unfertilised plots over time.

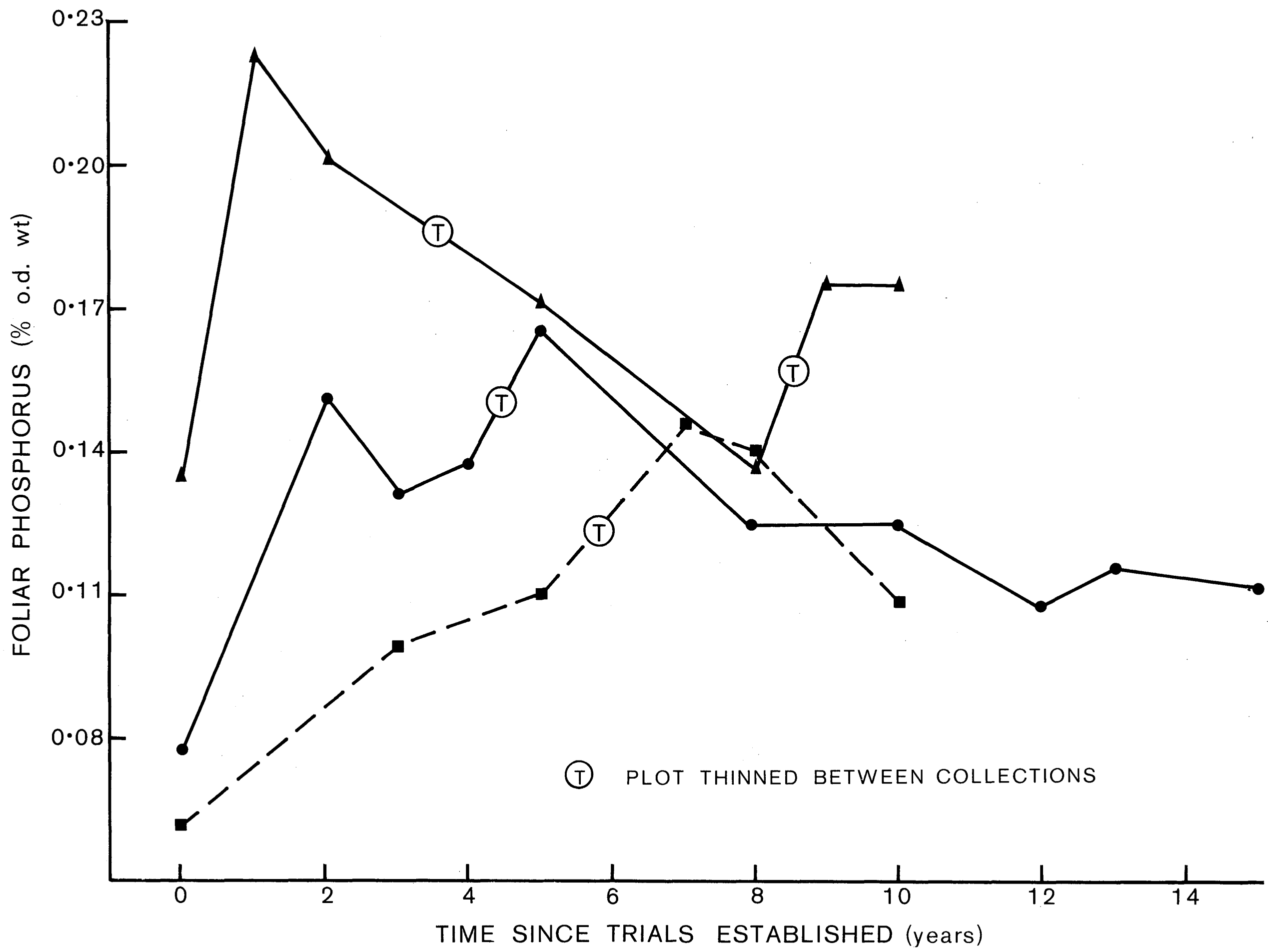

FIG. 2—Foliar phosphorus over time in three plots fertilised with 1250 kg superphosphate/ha.

It seemed possible that fitting a relatively simple mathematical model to the over-all data set could act as a test of the main effects (Table 2). Foliar phosphorus was the dependent variable. It was logarithmically transformed because its variance tends to increase with the mean. The trends identified from the graphs are shown to be strongly significant in the data set as a whole, and simply, account for a very high proportion of the total variation.

TABLE 2—Multiple regression surface of foliar phosphorus response to phosphorus fertiliser

Term	Coefficient	t
Y = Ln of 1000× foliar P concentration (% dry weight)		
Intercept	4.008	107.4
Foliar P at plot establishment	+0.004	11.9
Ln of 1+ cumulative amount of fertiliser (kg/ha)	+0.108	24.3
Ln of 1+ time since fertiliser applied (years)	-0.149	9.6
Thinned in the last 2 years? (dummy)	+0.104	6.0
Percentage variation explained	73%	
Addition of calendar year (dummy) Percentage variation explained	78%	

Individual calendar years were then included as dummy variables. This data set is ideal for studying effects of year-to-year variation since, because of the staggered starting dates between the blocks, fertiliser application time and calendar year are not strongly confounded. These dummy variables also effectively incorporate year-to-year climatic variation, albeit confounded with trial effects. Each year was found to differ significantly from the reference year (1967). However, the extreme deviation between any 2 years was only 0.015% P and, as can be seen from Fig. 3 where the annual deviations are shown relative to an over-all average foliar phosphorus, the average annual deviation is very small. Although there may be a systematic change in foliar phosphorus associated with either the change in sampling date (1974) or the change in laboratory method (1978), that change is very small and of no practical significance. Appoximately 5% more variation was explained by including the year-to-year effects.

More complicated models were built including interaction terms. However, these terms explained trivially small further amounts of total variation while introducing an undesirable degree of instability to the model surface.

DISCUSSION

The variation in foliar phosphorus over time in this trial series was satisfactorily explained in terms of the main trial effects. A very simple mathematical model, using terms that have a high degree of relevance to management, explained a high proportion of the total variation. These results are very encouraging, indicating as they do that problems with the use of foliage sampling do not lie with the relationship between foliage phosphorus and the driving variables – fertiliser and time. The standard error of

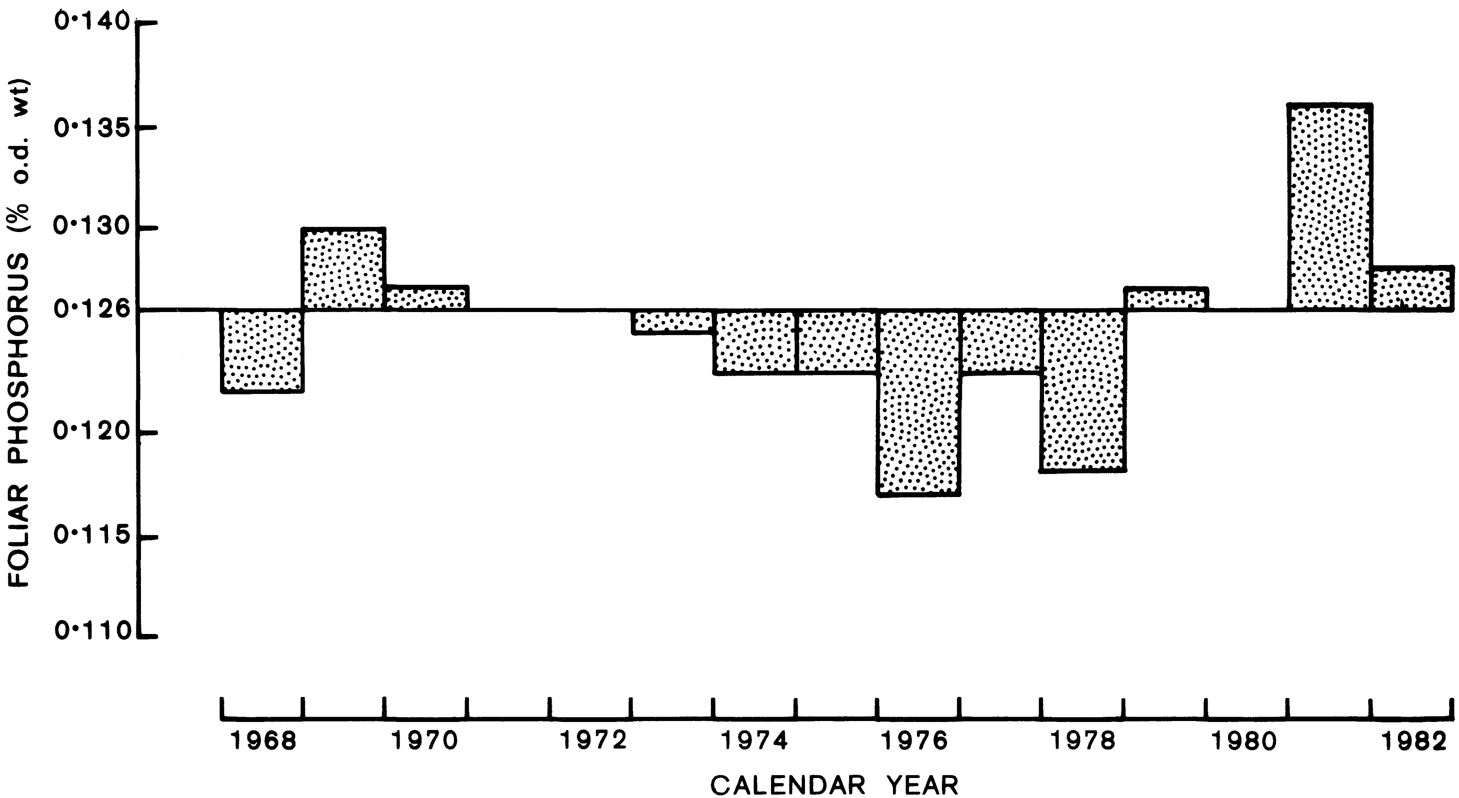

FIG. 3—Variations in foliar phosphorus associated with calendar year, expressed around the over-all mean.

the very simple model is equivalent to 0.015% P at the mean. That error could be slightly reduced by fitting the more complex models including interactions allowing, for example, for controls with a high initial phosphorus to decline over time. Thus the foliar phosphorus concentrations of samples collected from routine management operations should not, for this group of forests, differ from the expected (where expected is defined in terms of fertiliser applied, time, and so on) by more than 0.03% P. Deviations greater than this are, in the majority of instances, due to other factors.

The results proved to be unexpectedly insensitive to changes in date of sampling and, as hoped, insensitive to changes in analysis method. Mead & Will (1976) found that phosphorus concentrations showed a seasonal variation at some sites, with higher phosphorus concentrations expected from the mid-winter collections. It seems from these data that it would be possible to relax the tight controls we exercised over sampling time (15 February to 31 March). However, since other elements, notably nitrogen and magnesium, show a more marked seasonal variation, interpretation of analyses including these elements on material collected outside the standard sampling time would be difficult.

The unfertilised plots appear to tend over time to a concentration of 0.06% P. This seems to be the lower limit of phosphorus concentration below which *P. radiata* cannot survive. Trees at this concentration have very sparse canopies and are making very little growth (Hunter & Graham 1982). For the six blocks for which data are available, basal area (Mead & Gadgil 1978; Hunter & Graham 1982) of the controls at stand age 7 years is very closely related to foliar phosphorus at that age (Fig. 4). Hunter & Graham (1982) showed that growth declined progressively in those controls (at Whangapoua) that started with an average of 0.10% P and then declined to an average of 0.08% P.

There was an immediate increase in foliar phosphorus after fertiliser application. In this respect foliar phosphorus behaves like foliar nitrogen after nitrogenous fertiliser application. Although foliar phosphorus tends to decrease with time, the decline is not as rapid as with nitrogen (Hunter & Hoy 1983; Knight *et al.* 1983). The available nitrogen seems to be used within 1 year in expansion of canopy mass and nitrogen concentration can decline within that time to the same as in the unfertilised plots. Phosphorus concentrations in fertilised plots in this trial have, however, remained substantially above the unfertilised plots for 15 years, indicating either that the tree may have a different strategy for phosphorus use or that, unlike nitrogen, a continual residual source of phosphorus is available to the tree either from the direct residue of fertiliser or via biogeochemical cycling.

Woollons & Will (1975) pointed out that nitrogen fertiliser failed to give a response unless the later-aged stand to which it was applied had been thinned. Although none of our phosphorus experiments address this silvicultural question directly, if any similar phosphorus × thinning interaction existed we would certainly have discovered it by accident, in much the same way as Woollons & Will (1975) did for nitrogen. Yet, as far as we know, the ability of *P. radiata* to respond to phosphorus is independent of recent thinning. The rise in foliar phosphorus after thinning is, however, intriguing. Will *et al.* (1983) have shown that naturally shed foliage released 50% of its total phosphorus content over 2 years but only 20% of its nitrogen. A small study in which

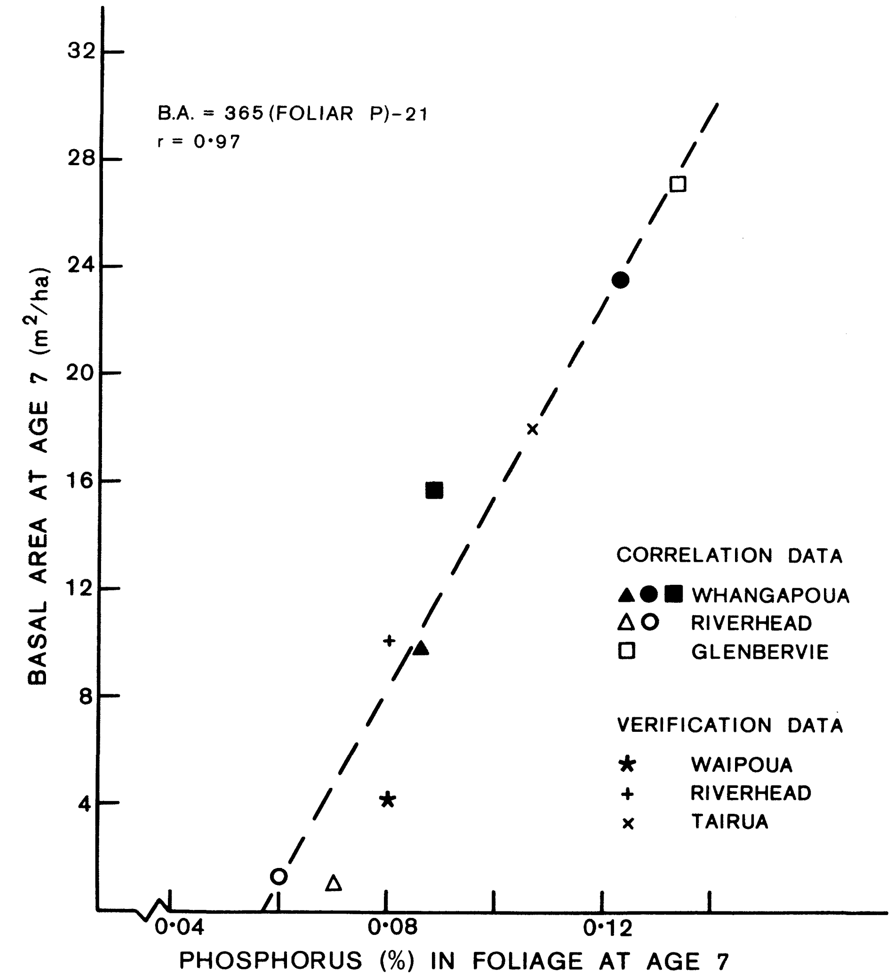

FIG. 4—Relationship between control foliar phosphorus and basal area at age 7 (correlation data from Hunter & Graham 1982; verification data from Hunter & Graham 1983).

foliage was collected from thinnings and prunings of known ages indicated that silviculturally severed foliage behaved similarly (Hunter unpubl. data). Thus, it may be that the response of thinned *P. radiata* to phosphorus fertiliser would be less than that of unthinned pine because of the phosphorus available from the slash. This behaviour could be managerially important, enabling us to delay fertilising by 2 years after a thinning and thereby reduce interest cost on the investment.

Miller (1966) working with loblolly pine (*Pinus taeda* L.) reported large changes in foliar nitrogen, phosphorus, and potassium associated with changes in weather, the absence of any stable period for sampling, and the probability of large year-to-year variation in results. In the moist, mild climate of the Auckland area *P. radiata* phosphorus concentrations seem to be remarkably stable. However, Mead & Will (1976) also found the seasonal interaction was least in their Auckland clay forest site but most marked in the drier Nelson site. Thus it may be that this finding of little climatic effect may not hold for other elements and other regions and, indeed, there is evidence that for nitrogen analyses of pine foliage collected from the drier parts of the South Island there is much greater year-to-year variation (Hunter unpubl. data).

With further development, the data presented in this paper could form the kernel of a predictive model encompassing amount and timing of fertiliser application. Such a model would be of considerable value in the financial management of phosphorus-deficient plantations. Testing the very simple model contained in this paper against foliar data from the newer series of trials reported by Hunter & Graham (1983) indicates that it performs well on the medium phosphorus-retention Riverhead site, overpredicts the high phosphorus-retention site where little foliar phosphorus response to fertiliser occurred, and underpredicts the low phosphorus-retention site (Fig. 5). Thus, without inclusion of soil variables the model cannot be extended beyond the clay soils of medium phosphorus-retention on which it was developed. Substitution for the initial foliar phosphorus term is also desirable. This could be achieved by a sub-model, probably driven by soil variables, that predicted the severity of initial phosphorus-deficiency to be expected on any site. As we pointed out previously (Hunter & Graham 1983) that will not be easy since this factor does not seem to be simply related to soil variables such as Bray P.

CONCLUSIONS

Foliage sampling *P. radiata* for its phosphorus content is a reliable and stable means of determining the trees' phosphorus nutritional status. Large irrational fluctuations in results from management sampling are therefore more probably due to poor supervision of the operation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of the many people who initiated this trial series and maintained it over 15 years. We also recognise the considerable difficulty experienced by local staff in keeping these trials free from contamination by aerially spread fertiliser during those years and are grateful for their success.

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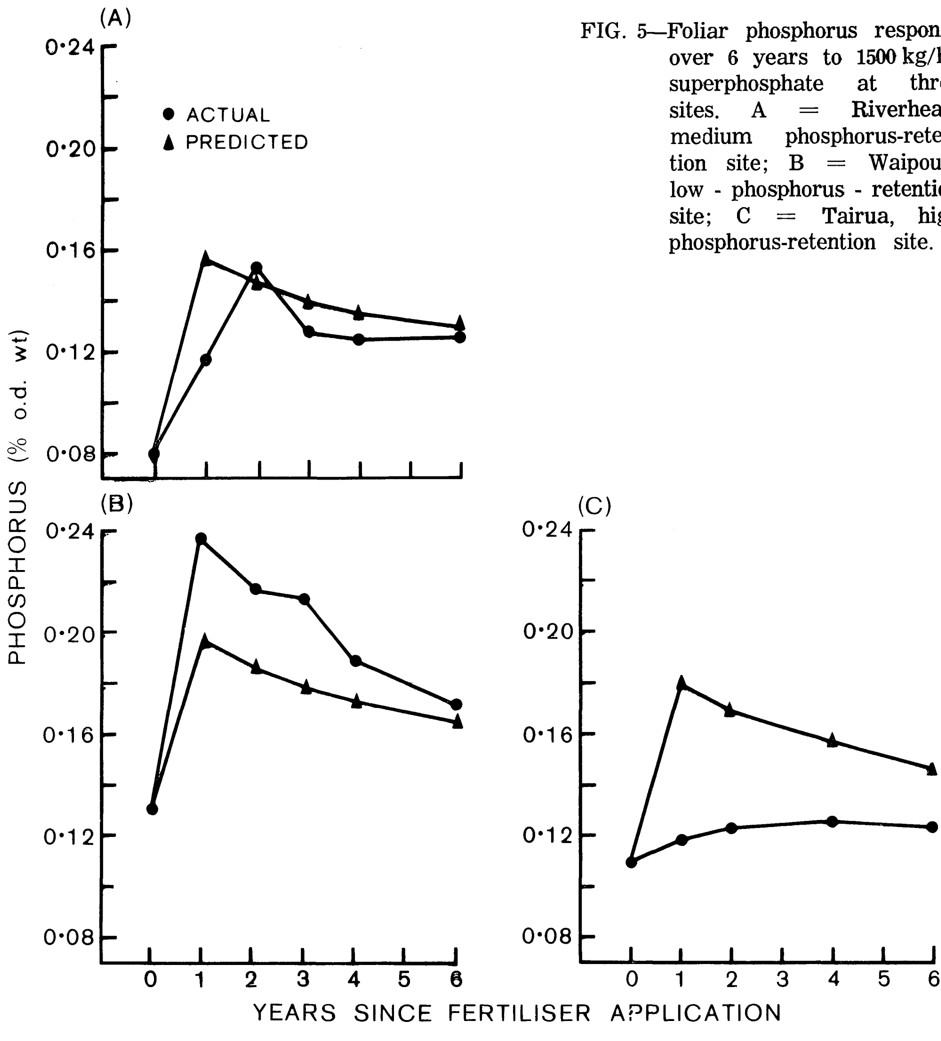

FIG. 5—Foliar phosphorus response over 6 years to 1500 kg/ha superphosphate at three sites. A = Riverhead, medium phosphorus-retention site; B = Waipoua, low - phosphorus - retention site; C = Tairua, high phosphorus-retention site.

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