WHAT SITE FACTORS DETERMINE THE 4-YEAR BASAL AREA RESPONSE OF PINUS RADIATA TO NITROGEN FERTILISER?

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ABSTRACT

The increase in basal area growth 4 years after fertiliser application in 44 trial comparisons in which 200 kg N/ha had been applied to **Pinus radiata** D. Don was regressed against soil and environmental variables and silvicultural treatments. Large positive responses tended to occur in stands less than 10 years old, particularly if growing on nitrogen-poor soils and if they had recently been pruned or thinned. Smaller positive responses occurred in older stands, and in stands on soils with total-nitrogen greater than 0.2%. Negative responses could occur if nitrogen was applied to stands on soils with Bray phosphorus less than 10 ppm.

The period of enhanced growth due to fertiliser was previously considered to last for 4 years but it now appears that may be followed by a period during which the treated trees grow slightly more slowly than the untreated. This affects economic evaluation of the response. The normal conclusion that fertiliser is best applied close to rotation age, is somewhat modified by the fact that response decreases with age of stand. Timing therefore appears to be a matter of economic indifference.

Keywords: fertiliser; nitrogen; growth response; **Pinus radiata**.

INTRODUCTION

Many nitrogen fertiliser trials were established throughout New Zealand between 1975 and 1984. This spate of activity was prompted by the publication in 1975 of a paper by Woollons & Will outlining encouragingly large responses to nitrogen fertiliser, and by the widespread perception that in the 1990s there would be a wood shortage in parts of New Zealand.

The trials were established partly as a co-operative effort between district foresters and the Forest Research Institute. No thought was originally given to establishing a balanced series of trials. It was intended to interpret results in the light of the soil types and individual stand conditions to which they applied. For several of the trials this has been done (Hunter 1982; Hunter & Hoy 1983; Hunter 1984). However, it is necessary to generalise from a collection of fertiliser trials in order to determine the factors that seem to affect the magnitude and likelihood of a fertiliser response. Otherwise those trials are essentially useless to a manager whose soil type or crop condition differs even slightly from those represented by the trials.

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Consequently, attempts to generalise are a fairly common feature of fertiliser trial work around the world. Crane (1981) found an inverse relationship between response and foliar nitrogen in his trials with *P. radiata* in Australia. Rosvall (1979) used only terms that would be freely available to managers (site index, latitude, altitude) in constructing a model for mixed pine forest in Sweden. He found that response first increased with age (up to about age 50) and then decreased. Radwan & Shumway (1983) found that inadequate soil phosphorus and high soil nitrogen could limit response to nitrogen fertiliser in western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Peterson *et al.* (1984) likewise found a relationship between Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) response and soil nitrogen.

The objective of this study was to attempt to build a generalised model of nitrogen fertiliser response in *P. radiata* from the data available.

TRIAL SELECTION

Two standard designs were used extensively in the trials that had been established throughout the country – a rates of nitrogen fertiliser trial, and a nitrogen × phosphorus factorial. In the nitrogen rates trials, nitrogen fertiliser was applied to plots of at least 0.09 ha at the rate of 0, 100, 200, and 300 kg N/ha. A minimum of three replications was used. In the nitrogen × phosphorus factorials, fertiliser was applied to similar-sized plots at the rate of 0, 200 kg N/ha, 100 kg P/ha, and 200 kg N + 100 kg P/ha, similarly replicated. The workplans for both trial designs required annual assessment of basal area for 4 years, collection of soil samples before fertiliser application, and annual collection of foliage samples.

In addition several trials were established with silviculture and nitrogen fertiliser as treatments. In the simpler of two trial designs the interaction of thinning (T) and nitrogen fertiliser at 200 kg N/ha were tested. The more complex design was a complete factorial in thinning, pruning (Pr), and nitrogen fertiliser at 200 kg N/ha. Similar measurement, soil sampling, and foliage collection standards were adhered to.

The factors common to all trial designs were the existence of a treatment in which 200 kg of nitrogen alone was applied and a treatment completely without fertiliser. As we have shown in other papers (Hunter & Hoy 1983; Hunter 1982) the pattern of basal area response to nitrogen fertiliser is complex. Immediately after fertiliser application basal area growth accelerates relative to the control, reaching a peak increment difference after only 1 or 2 years. Thereafter the relative increment difference declines until after 4–5 years current basal area increments in both control and fertiliser plots are similar. In the interests of simplicity it was decided to work with the cumulative response only, i.e., the basal area response after 4 years, in the search for determining site factors. Basal area after 4 years in the trials was analysed by covariance on initial basal area using GENSTAT (1983). We had found previously that covariance analysis reduced error variance markedly. The simple difference between the adjusted means of basal area with and without fertiliser 4 years after application is defined, for the purposes of this paper, as the fertiliser response. In the silvicultural trials the thinned and unthinned parts were analysed separately because covariance analysis on the whole trial, where the covariate is affected by treatment, i.e., thinning, makes a nonsense of the results. The fertiliser response is the difference between plots with identical silvicultural treatment differing only in fertiliser. Thus each fertiliser × thinning trial yields two comparisons, and each three-factor trial (fertiliser × thinning × pruning) yields four comparisons.

METHODS

Soil samples were collected at each site prior to fertiliser application. A couple of trials which had a basal phosphorus dressing at time of nitrogen fertilising were excluded from the data set because that phosphorus application would not have been reflected in the soil analyses. For this reason, neither the moderately deficient site described by Hunter & Hoy (1983) nor the trial of Mead *et al.* (1984) were included. However, trials from chronically phosphorus-deficient forests where phosphorus fertiliser had been applied some time previously were included because that fertiliser should be reflected in the soil analyses. Soil samples were eventually analysed for total-nitrogen, carbon, pH, percentage clay, Bray phosphorus, phosphorus retention, and Bray cations (Nicholson 1984). Not all trials had originally been analysed for all characteristics, particularly phosphorus retention and Bray cations. Some later resampling was necessary to ensure that each site had a complete complement of determinations: these samples were taken from control plots and, fortunately, in the event the determinations made on these samples proved unimportant to the over-all result. Soil available-nitrogen was determined by anaerobic mineralisation (Waring & Bremner 1964).

Recently matured foliage was collected from secondary branches in the upper crown each autumn and analysed for nitrogen and phosphorus (Nicholson 1984).

Average annual temperature and rainfall for each trial site were extracted from climatological summaries (New Zealand Meteorological Service 1983). We would have wished to use temperature and rainfall at and after fertiliser application but unfortunately some of our records of application date and of the weather were neither accurate nor specific enough to enable us to do so.

There proved eventually to be 32 suitable trial sites (Fig. 1) yielding 44 individual comparisons.

RESULTS

Basal Area Response

Basal area response averaged 1.35 m^2/ha and ranged from –1.1 m^2/ha to 5.0 m^2/ha. All the larger responses (positive or negative) were highly significant statistically. Typically responses less than ± 0.8 m^2/ha were not significant. The largest responses occurred in trials that had received fertiliser at an early age, usually in conjunction with some silviculture, and were on soils poor in nitrogen such as the sand soils. Thus two of the largest responses (averaging 4.4 m^2/ha) occurred in stands that were 8 and 5 years at time of fertiliser application, had been thinned and pruned, and were on soils with 0.03% N and 0.01% N, respectively (Rabbit Island, Woodhill N×Pr×T). Small positive responses were associated with older stands or better soils. Negative responses averaging –0.9 m^2/ha occurred in four trials (Ngaumu, Gwavas, Kaweka, and Waimihia). The only distinguishing feature about these trials

FIG. 1—Trial locations.

was the low soil phosphorus (10, 4, 7, and 7 ppm respectively) and a lowering of foliar phosphorus after nitrogen fertiliser application. The first three trials were from the N×P series and showed, in their other treatments, a weak response to phosphorus alone but a positive response to nitrogen when applied in conjunction with phosphorus. The Waimihia trial was a nitrogen rates type and showed a strong negative linear effect across the rates. It had an additional treatment in which phosphorus (and other elements) were applied with 200 kg N/ha and that treatment had a small positive response. Thus it seems fairly conclusive that low available-phosphorus can limit nitrogen responses even to the extent of causing a deterioration in growth after application of nitrogen fertiliser.

In the younger silviculture trials (Woodhill N×Pr×T, Kaingaroa and Matea N×Pr×T) the response to nitrogen in the thinned plots was greater than in the unthinned, and in the pruned greater than in the unpruned. In the later age trials (Santoft N×T, Kawerau N×T, and Kaingaroa N×T) where thinning took place at 19, 20, and 15 years respectively the response pattern was not so clear. However, analysis of the response in the unthinned plots was greatly complicated by natural mortality.

Model Fitting

With basal area response as the dependent variable, multiple regression analysis was conducted with the following independent variables: soil total-nitrogen, soil mineralisable-nitrogen, soil carbon, pH, percentage clay, Bray phosphorus, phosphorus retention, Bray cations (calcium, potassium, and magnesium), age of trees at fertiliser application, initial basal area, stand site index, average annual rainfall and temperature, whether or not the stand had been pruned or thinned within 1 year prior to fertiliser, and foliar nitrogen and phosphorus in the control plots. It rapidly became apparent that there was considerable fluctuation from year to year in foliar nitrogen and so an average of all available results was constructed and used instead. The simple correlation coefficient between basal area response and each of these variables is given in Table 1.

Certain terms, such as pH and soil calcium, contributed nothing to any model surface. Others were intercorrelated and could only be used as alternatives. For example, soil total-nitrogen was correlated 0.88 to carbon, 0.89 to available nitrogen, and 0.66

TABLE 1—Correlation coefficient between 4-year basal area response to nitrogen and possible determining variables

Soil total-N, -0.36	Soil available-N, -0.34	Foliar N, -0.50
Soil Bray P, +0.25	Soil P-retention, -0.30	Foliar P, +0.19
Site index, +0.03	Initial basal area, -0.18	Start age, -0.25
Rainfall, -0.23	Temperature, +0.22	Clay %, +0.24
Thinned?, -0.04	Pruned?, +0.42	Pr×T, +0.30
Soil Mg, -0.08	Soil Ca, +0.01	Soil K, -0.22
Soil carbon, -0.27	pH, 0.00	

to foliar nitrogen. Available nitrogen was also correlated 0.66 to foliar nitrogen. Soil nitrogen was correlated –0.59 to temperature and +0.25 to rainfall and excluded both of them from the model. Although average foliar nitrogen had the highest simple correlation, when fitted as alternatives in models with an otherwise identical structure soil total-nitrogen had the highest t value followed by soil available-nitrogen and foliar nitrogen. Six percent of the explained variation was lost substituting soil available-nitrogen for total nitrogen and 10% substituting foliar nitrogen. The model finally selected is presented in Table 2.

The model accounts for 66% of the total variation and has a standard error of 0.8 m^2/ha around the mean response of 1.35 m^2/ha.

TABLE 2—Determining factors in 4-year basal area response to nitrogen

Factor		t
Constant		6.2
1/(1 + soil total-N)		5.1
Ln soil Bray P		3.1
1/age at fertilising		4.3
Clay %		3.3
Prune	dummy variables	4.3
Thin		2.1
Thin × prune		5.2

Four-year basal area response is the independent variable.

DISCUSSION

There has been general dissatisfaction with the most readily available predictors of nitrogen fertiliser response – soil total-nitrogen and foliage total-nitrogen. Many tree species seem to respond to varying nitrogen supply rapidly and massively by adjusting the size of their needles/leaves or the quantity in their canopy (e.g., for Douglas fir – Brix 1981; for Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire) – Miller & Miller 1976). After large increases in nitrogen supply, foliar nitrogen can return to its previous level rapidly (Hunter & Hoy 1983). That makes it an insensitive indicator of relative nitrogen shortage. Research effort has been expended in improving these predictors. Van den Driessche & Webber (1977) found the arginine and guanido concentrations in the root and bark of Douglas fir a better indicator of nitrogen response than foliage concentration.

Even more effort has gone into attempting to find an estimate of soil available-nitrogen (Keeney 1980). Lea & Ballard (1982) found that neither aerobic nor anaerobic mineralisable nitrogen correlated well with fertiliser response in loblolly pine (*Pinus taeda* L.). Fractionating the nitrogen in foliage and incubating soil are expensive and time-consuming operations which may be difficult to put into management practice (Cotrufo & Wells 1984). Thus the means to improve our measurement of relative nitrogen shortfall, which is the purpose of soil and foliar nitrogen measurement, is not obvious.

The fault may not lie with the measure of nitrogen shortfall, however. Perhaps we should expect nitrogen response to be variable. Much will depend on the weather during and after the fertiliser application. Hot and dry weather or very heavy rain could both result in losses. The term "% clay" included in this model may be a reflection of this aspect. Relative to coastal sands the clay soils tend to be more acid, have slower infiltration rates, have exchange sites for nitrogen, and are more likely to be moist at the surface when the fertiliser is applied. All of these factors point to lower losses through leaching or volatilisation and a longer residence time in the soil. In addition, on top of the loss of precision due simply to poor fit, several variables which we now feel probably affect nitrogen response significantly were not measured consistently in this trial series – the amount of needle litter on the forest floor, and the weed biomass at time of fertiliser application. In one small study at the Santoft N×T trial almost the whole of the applied 200 kg N/ha seemed to be located in the substantial litter layer 1 year after application (Hunter, unpubl. data), yet younger stands and some of the more intensively tended older stands have a much shallower litter layer to intercept the applied fertiliser. Stimulation of weed growth after nitrogen fertiliser application has often been observed visually but not quantified. However, in a recent trial in 10-year-old trees where the interaction of nitrogen fertiliser with chemical control of pampas grass was tested, tree response to nitrogen where the weeds were eliminated was greater than where they remained.

Relatively few other models have silviculture as an effect. That this model incorporates, however simplistically, terms in thinning and pruning is a measure of the data yielded by the aggressive silvicultural intervention in the average New Zealand *P. radiata* stand. It is a pity that our data are not sufficiently detailed to enable us to explore this aspect beyond the level of simple dummy variables. The model will predict a substantial response in an unthinned stand provided that the stand is young and on a low nitrogen soil. This is consistent with the data: the Woodhill N×Pr×T trial gave a response of 1.6 m^2/ha when unthinned and unpruned. A larger response is predicted if the stand is either thinned or pruned but if both operations take place together the response is reduced. It must be remembered that each of these responses is relative to an equivalent silvicultural treatment without fertiliser. In terms of declining actual gross productivity, the treatments would rank unthinned unpruned > pruned (usually) > thinned > thinned and pruned together. Nitrogen fertiliser tends to increase foliage and to help the stand recover from the silvicultural "damage" to its photosynthesising canopy. Hence the tendency to low responses in some unthinned unpruned plots where the canopy may have, in developed stands, little room to expand. Response increases with increasing opening of the canopy, up to a point, after which it seems to decrease again. Normal thinning and pruning at age 5 reduce a *P. radiata* canopy by up to 90% (Hunter *et al.* 1985) and it may be that there is insufficient foliage mass left to take up and store the nitrogen and insufficient buds remaining to make maximum use of its canopy-expanding properties.

This paper is not the place for a full discussion of the management significance of these findings because the economics involved are complex and many different scenarios are required. However, some limited comment is desirable.

Determining the value of a short-term fertiliser gain depends crucially on the assumption that the 4-year growth gain can be harvested at rotation age. If we correctly understand the mechanism of response, particularly in relation to silviculture – that it increases the rate of canopy recovery – then there seems to be no theoretical reason to suppose that the gain would be totally eroded. However, we are now in a position to update results from some of the earlier trials – for example, that of Hunter & Hoy (1983). It seems that in this particular trial, after the positive response had ceased there was a period of readjustment in which the trees that had received fertiliser actually grew more slowly than those that had not (Fig. 2). As a result, part of the growth gain predicted from the 4-year response was lost. The response declined from a peak of 5.3 m^2/ha 5 years after fertiliser application to 3.7 m^2/ha 10 years after – a loss of 30%. Most of the trials discussed in this paper either have not been measured since year 4, have been measured only infrequently, have been thinned again, or were established too recently to shed light on this point. However, in one other trial for which we have good data (Woodhill 1) this trend is also detectable. Overseas evidence on this point is conflicting. In the United Kingdom (C.M.A. Taylor, pers. comm.) out of a set of four trials one behaved similarly, one showed an increasing response, and two continued

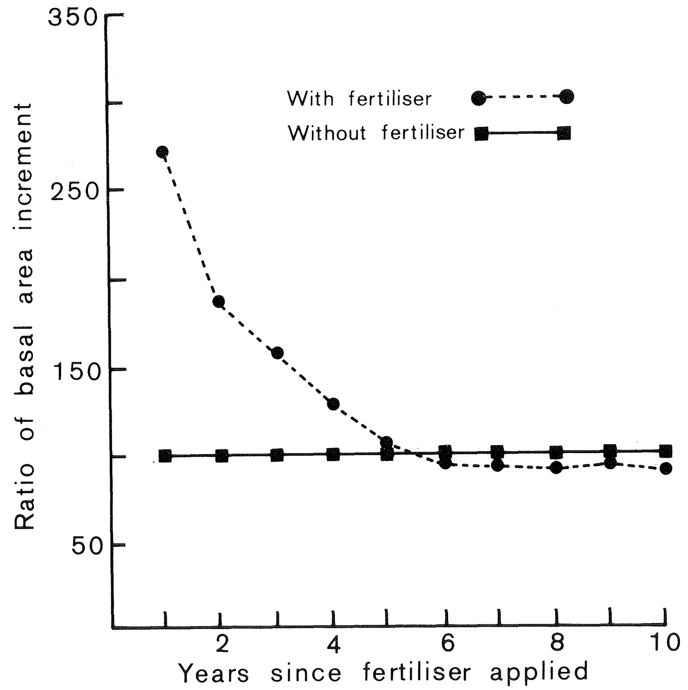

FIG. 2—Ratio of basal area growth in plots with nitrogen fertiliser to plots without fertiliser over time.

to grow at the same rate as the control once the fertiliser effect had culminated. Thus in evaluating the results presented in this paper for management purposes it is probably wise to consider the predicted response as the maximum likely.

Optimising the time of fertiliser response poses peculiar problems. The compounded cost of the fertiliser declines approximately parallel to the projected value of the fertiliser response as the magnitude of response declines with age. In Fig. 3 the compounded cost of fertiliser is calculated from a material cost of \$250 compounded at 10% to rotation age of 30 years. The value of the fertiliser gain is calculated by assuming that each square metre of basal area gain would be worth \$1000. That is equivalent to a stumpage of \$60–\$70/m^3 at age 30. However, the specific assumptions behind this figure are not important; the crucial point is that it requires only a small change in relative costs or in the shape of the model surface to greatly alter the true optimum timing of fertiliser application. Given the poor precision of the model surface, and the uncertainties associated with cost projection, all timings appear to be approximately equal in the prospect of profitability. Fertiliser timing seems therefore to be a matter of indifference. These results are somewhat at variance with the general conclusion of similar studies, that fertiliser is best applied close to rotation age. Our conclusion is further amplified by the fact that silvicultural treatment is increasingly rare towards rotation age and responses in the absence of silviculture are uncertain and small.

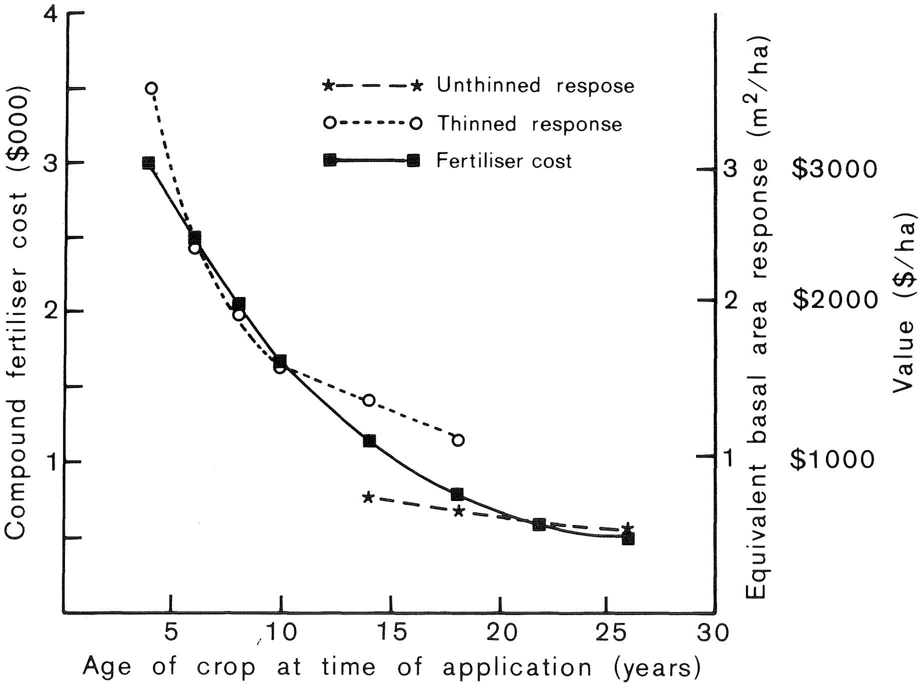

FIG. 3—Cost and value of nitrogen fertiliser by age of crop at time of application.

CONCLUSIONS

We conclude that the maximum basal area responses and hence volume responses to nitrogen fertiliser will occur in young crops of *P. radiata,* particularly those growing on nitrogen-poor sites and currently undergoing silvicultural treatment. Investment in older crops, even if tended, and in crops growing on sites with high nitrogen status is less advisable and less certain, and nitrogen fertiliser on low-phosphorus sites can actually be detrimental.

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