GROWTH RESPONSE OF PHOSPHORUS-DEFICIENT PINUS RADIATA TO VARIOUS RATES OF SUPERPHOSPHATE FERTILISER

I. R. HUNTER and J. D. GRAHAM

Forest Research Institute, New Zealand Forest Service,
Private Bag, Rotorua, New Zealand

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ABSTRACT

Superphosphate fertiliser was applied at various rates to plots of phosphorus-deficient **Pinus radiata** D. Don (radiata pine) in four forests in the Auckland area. Soil analyses showed that most of the plots had a low level of extractable phosphorus (Bray & Olsen) prior to fertiliser application. Foliar phosphorus concentrations remained deficient in the controls but were raised to adequacy by fertiliser in the treated plots. Analysis of the growth response was made difficult by the lack of replication within all sites, but a series of partial statistical analyses strongly indicated that height growth was positively affected by fertiliser. On more fertile sites the fertiliser acted to maintain a high site index while on less fertile sites site index was improved. Large growth improvement was obtained at the lowest rate tested (625 kg superphosphate/ha). Higher rates gave little further increase in growth. Basal area growth was also increased by fertiliser. The higher rates (1250 and 2500 kg/ha) generally gave greater growth than the lower rate (625 kg/ha) but each increase in amount brought a smaller increase in basal area growth.

INTRODUCTION

Extremely phosphorus-deficient radiata pine trees were identified in Riverhead Forest (North Island, New Zealand) in the early 1950s. Their growth was greatly improved by application of large amounts of superphosphate, i.e., 2250 kg/ha (Weston 1956). Since then it has been realised that most of the Auckland region radiata pine plantations on clay soils tend to be phosphorus deficient and use of fertiliser has become widespread. The normal practice is to apply 1000 kg superphosphate/ha (Will 1981) when the phosphorus concentration in foliage samples collected during late summer is less than 0.13% (Will 1978). Early trials did not test the response to this method of treatment (Weston 1956). A later trial series included this type of treatment and a range of alternatives, but to date only a brief report has appeared on the series (Mead & Gadgil 1978). Flinn *et al.* (1979) reported significant gains in basal area after similar rates of superphosphate application on yellow podzolic soils in South Australia.

Superphosphate fertiliser has recently increased in price very markedly. Therefore, although the trial series has many more years to run, it is an opportune moment to

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fully describe the trial and to see whether information to date can be used to improve the cost-effectiveness of regular fertiliser application.

Since the experiment consists of groups of unreplicated plots with a variable measurement history, interpretation of growth differences is difficult. Soil and foliage analyses had to be examined to confirm that growth of radiata pine on these sites is limited mainly by phosphorus deficiency before statistical analysis of growth response was attempted.

METHODS

Experimental Design

A phosphorus-rates fertiliser experiment was established in radiata pine stands in four forests in the Auckland region between 1967 and 1973 (Table 1). The stands were thinned at the same time as the compartments in which they stood. There was little uniformity between blocks in this treatment, as shown in Table 1.

Fertiliser Treatments

Six fertiliser treatments are common to all seven blocks. As the later blocks were established extra treatments were included (Table 2) allocated at random. Each plot has a total area of 0.16 ha including the surround, and an inner measurement plot of 0.0405 ha in which all trees are numbered and banded at breast height. Superphosphate fertiliser (approx. 10% phosphorus by weight) was applied evenly by hand over the whole plot.

Site Description

All the blocks (groups of plots) are on clay soils. Blocks 1, 2, and 3 in Whangapoua Forest are on a firm, coarse, blocky, structured clay, tending to massive at depth, derived from Hamilton ash beds, over very old andesitic tuffs (W. Rijkse pers. comm.). Block 1 is relatively flat (less than 10° slope). Blocks 2 and 3 are steeper (20–30° slope).

Block 4 in Glenbervie Forest is situated on a firm clay with a strong medium blocky structure derived from recent reweathering of old deep redweathered clays. Block 5 in Maramarua Forest is on a very firm, very coarse, structured silty clay derived from intense weathering of greywacke.

Blocks 6 and 7 in Riverhead Forest are on a very firm, almost massive, medium blocky, structured silty clay tending to massive at 50 cm from the surface. This soil is similar to that mapped as a Waikare clay loam (N.Z. Soil Bureau 1968) which is derived from siliceous claystones. Slopes within the site vary around 10° to 20°.

Analyses

Soil

Topsoil samples were collected from each plot at most sites prior to fertiliser application. The samples were analysed for Bray P (Bray & Kurtz 1945), Olsen P (Olsen *et al.* 1954), phosphorus retention and pH (Blakemore *et al.* 1972), percentage fines (Piper 1950), and percentage nitrogen (Searle 1974). Some analyses were made on subsequent collections from control plots.

TABLE 1—Location, establishment date, and thinning schedule of each trial block

Block	Forest	Date of trial establishment	Crop age at establishment (years)	Thinned* at establishment	1st Thinning		2nd Thinning	
					Time (years)	Degree*	Time (years)	Degree*
1	Whangapoua	1967	6	No	4	HT		
2	Whangapoua	1967	6	No	3	HT		
3	Whangapoua	1969	8	No	2	HT		
4	Glenbervie	1970	5	No	3	HT	8	LT
5	Maramarua	1971	8	No	5	MT		
6	Riverhead	1973	6	LT	6	HT		
7	Riverhead	1973	6	LT	6	HT		

* LT = Light thinning (less than 20% basal area removed)
MT = Moderate thinning (20–50% b.a. removed)
HT = Heavy thinning (more than 50% b.a. removed)

TABLE 2—Fertiliser treatments

Abbreviation used in text	Fertiliser treatment	Found in blocks
0 or control	No fertiliser	1–7
625	625 kg superphosphate/ha at trial establishment	1–7
1250	1250 kg superphosphate/ha at trial establishment	1–7
2500	2500 kg superphosphate/ha applied at trial establishment	4–7
625*2	625 kg superphosphate/ha at trial establishment and again after 10 years	1–7
625*4	625 kg superphosphate/ha at trial establishment and repeated after 5, 10, and 15 years	1–7
625D	625 kg superphosphate/ha applied 5 years after trial establishment	1–7
625P%	625 kg superphosphate/ha applied at establishment and reapplied if annual foliage samples contain less than 0.12% P or between 0.12 and 0.13% P in 2 consecutive years	3–7
1250P%	1250 kg superphosphate/ha with same criteria as 625 P%	6–7

Foliage

Samples were collected in winter from the recent foliage in the upper crown of seven trees per plot. Foliage was dried to constant weight at 70°C and ground; after dry ashing, phosphorus, calcium, magnesium, and potassium were brought into solution by digestion with hydrochloric acid. Phosphorus was determined by the vanadomolybdate method; calcium, magnesium, and potassium by atomic absorption spectrophotometry; and nitrogen by micro-Kjeldhal, of ground foliage samples.

Statistical

Breast height diameters of each tree in the measurement plots, and a sample of tree heights, were entered into the computerised permanent sample plot system (McEwen 1979) where basal area per hectare and mean top height (height of the 100 largest-diameter trees per hectare) were calculated. Where possible (e.g., at Whangapoua and Riverhead) analysis of variance of these traits with initial size as a covariate was performed and approximate response surfaces were calculated (Snedecor & Cochran 1967). Much of the data could not be treated this way. Multiple regression surfaces (IBM 1966) were calculated to draw in that information. Between two and four short increment periods were selected per plot. Deviations from the regression surface were inspected to locate obvious serial correlation between observations caused by this procedure but serial correlation appeared to be at a low level.

RESULTS AND DISCUSSION

Soil Analyses

Six of the blocks had little Bray and Olsen extractable phosphorus in their topsoil (Table 3). Block 4 (Glenbervie) had a higher over-all mean extractable phosphorus but considerable variation between plots. Retention of applied phosphorus was medium in most blocks but low in Block 5 (Maramarua). Sites of very high phosphorus retention are not represented in this series (N.Z. Soil Bureau 1972). Soil total nitrogen concentrations varied markedly between blocks; Block 4 had medium concentrations whereas Blocks 1, 2, 3, 6, and 7 were low, and Block 5 was very low (N.Z. Soil Bureau 1972). All the soils are strongly acid (Taylor & Pohlen 1970).

TABLE 3—Results of chemical and physical analyses on topsoil samples (from unfertilised plots)

Block	Bray P (ppm)	Olsen P (ppm)	P retn (%)	Percentage fines silt and clay	N (%)	pH
1	4.8	3.3	56	89	0.21	4.6
2	2.3	1.7	57	90	0.26	5.0
3	NA	3.2	64	87	0.30	4.6
4	12.5	6.4	59	95	0.48	5.0
5	2.4	3.4	15	NA	0.05	4.4
6	1.9	1.5	40	NA	0.13	4.8
7	1.9	1.6	43	NA	0.14	4.8

NA = Not available

Foliar Nutrient Concentrations

The mean concentration of phosphorus in the first five annual foliage samples from the control plots in each block (Table 4) was below the critical 0.13% P identified by Mead & Gadgil (1978). Application of fertiliser caused a rise in foliar phosphorus to an over-all mean of 0.13% P or above in fertilised plots in the first 2 years after application, except in the Riverhead plots grouped into Block 7. Nitrogen concentrations were adequate in Blocks 1 to 4, low to marginal in Blocks 6 and 7, and deficient in Block 5 (Hunter 1982). Potassium, calcium, and magnesium concentrations were adequate in all blocks (Will 1978).

Thus the radiata pine to which phosphorus fertiliser was applied were growing in a soil with low levels of available phosphorus, were nutritionally deficient in that element at all sites, but were moderately well supplied with most other nutrients.

Height Growth

Plots in Blocks 1, 2, and 3 at Whangapoua are in the same compartments and contain trees of the same age. Block 3, however, was fertilised and first measured for height 2 years later than Blocks 1 and 2. There is therefore no appropriate initial height covariate for later measurements. Mean top heights for the six common plots (i.e., excluding the 625P% plots from Blocks 2 and 3) for the years 1972, 1977, and 1979 were analysed (Table 5).

The results in Table 5 show that fertiliser has had an effect on height growth and that the difference between the control and the fertilised plots has increased with time. Initially (1972) the mean of the three plots with delayed fertiliser application

TABLE 4—Foliar phosphorus in control and fertilised plots, and other foliar element concentrations in fertilised plots

Block	Foliar P* in control (% dry wt)	Foliar P† in fertilised plots (% dry wt)	Other elements in all fertilised plots (% dry wt)			
			N	K	Ca	Mg
1	0.08	0.13	1.58	0.91	0.23	0.15
2	0.12	0.16	1.47	1.00	0.19	0.14
3	0.09	0.14	1.40	0.97	0.18	0.14
4	0.12	0.21	1.60	0.95	0.21	0.12
5	0.08	0.18	1.16	1.18	0.19	0.14
6	0.07	0.13	1.31	0.95	0.19	0.12
7	0.06	0.10	1.35	0.95	0.17	0.11

* Mean of first 5 years after plot established

† Mean of first 2 years after treatment

TABLE 5—Effect of fertiliser treatment on mean top height (m) for three ages in Blocks 1, 2, and 3

Treatment	Year (Age)		
	1972 (11)	1977 (16)	1979 (18)
0	16.5_{ab}	21.9_{a}	22.8_{a}
625D	15.7_{a}	22.8_{a}	25.6_{ab}
625	19.3_{b}	26.7_{b}	28.3_{b}
625*2	18.9_{b}	26.0_{b}	28.0_{b}
625*4	19.0_{b}	26.2_{b}	27.6_{b}
1250	18.7_{b}	26.0_{b}	28.7_{b}

Different subscript letters indicate significant differences between treatments ($p = 0.05$)

was less than the control. After fertiliser was applied (1972–74) growth increased, they overtook the control plots, and in 1979 just failed to be significantly taller than them.

In Fig. 1 the control, 1250, and 625D mean top heights are illustrated for ages 6 to 18 in Blocks 1, 2, and 3. Also shown is a curve for site index 30 m (BT SI 30) from the regional height-age tables (Burkhart & Tennent 1977). The fertilised plots (represented by the 1250 plots) have maintained the site index that was indicated at age 6 whereas the control plot has fallen progressively further behind.

The Riverhead site (Blocks 6 and 7) with two internal replications provided the opportunity for a further analysis of variance. Initial height measurements were available and provided a covariate. After covariance there was a significant effect of fertiliser on mean top height 5 years after fertiliser was applied. Since several of the treatments were identical in the early years (i.e., 625D = 0, 625*2 = 625) plots that had received similar amounts of fertiliser are grouped together in Table 6. Here fertiliser had increased apparent site index.

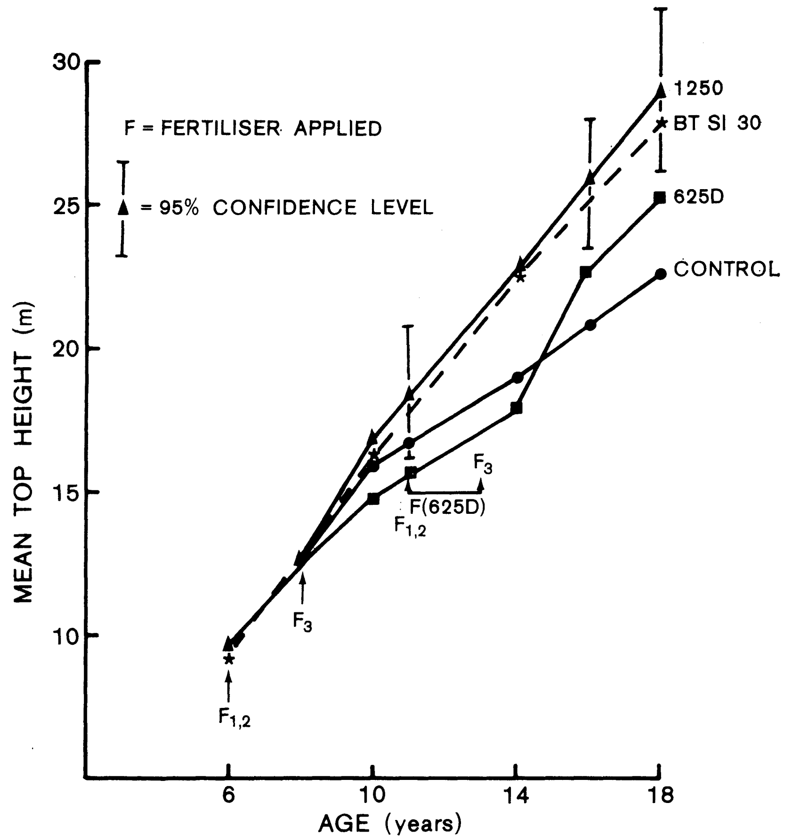

FIG. 1—Height growth (m) in Blocks 1-3, Whangapoua Forest

TABLE 6—Covariance adjusted mean top heights (m) in Blocks 6 and 7 (5 years after fertiliser application)

Treatment	Number of plots	Over-all mean
Control	4	9.32 $_{a}$
625	6	11.58 $_{ab}$
1250	4	11.88 $_{b}$
2500	2	13.32 $_{b}$

A stepwise multiple regression of annual height increments was calculated in order to include data from Blocks 4 and 5. The regression (Appendix 1.1) surface tended to confirm the result found in the analyses of variance: there were no practical differences in height growth between fertiliser rates.

A second regression analysis (Appendix 1.2) in which all fertilised plots were contrasted with all unfertilised plots showed that the significance of the fertiliser effect was greatly increased by this combination. On average, annual height increment in

10-year-old trees which had received fertiliser would be 27% greater than in trees which had not.

The lack of significant differences between fertiliser rates is possibly a result of two factors:

(a) Apparent differences are actually fairly small. With the exception of the contrast between the 2500 plots and the others at Riverhead, differences are generally less than 1 m.

(b) Least significant differences are large (greater than 2 m). The ever-present inaccuracy of field measurements of height (Whyte & Mead 1977) is possibly one contributory factor.

Basal Area Growth

Analysis of variance of nett basal area growth in this trial is more difficult than for height growth because of the variable thinning treatment. The simplest analysis structure is provided by the internally replicated unthinned Riverhead site (Blocks 6 and 7). Mead & Gadgil (1978) reported results 3 years after fertiliser application, showing that basal area was 50% greater in the 625 and 1250 plots. Analysis of covariance on results at 6 years showed that there was still an extremely significant effect of fertiliser on basal area (Table 7). The covariate was basal area at establishment. Basal areas in the control plots increased by only 60% between the 3- and 6-year measurements whereas they doubled in most fertilised plots. The relationship between the growth of some of the treatments is difficult to understand. It is not apparent why the 1250 treatment should give relatively little improvement over the 625 when the 2500 treatment is superior to both. The reason may lie in chance irregularities caused by having a large number of treatments and few replications at this site.

TABLE 7—Effect of fertiliser on basal area in Blocks 6 and 7 (6 years after trial establishment)

Treatment	Number of plots	Basal area* (m^2/ha)
0	4	8.18_a
625	6	14.31_b
1250	4	14.20_b
2500	2	17.15_c
625P%	2	14.80_b
1250P%	2	12.47_b

* Data analysed by analysis of covariance; different subscript letters indicate significant differences ($p = 0.05$)

Differences between rates of fertiliser appeared to be more marked for basal area than for height. The possibility of treatment × site interaction is therefore probably higher. Because of the lack of internal replication, opportunities to test for its presence were limited. Therefore, making use of the equality of treatment in the early years of the trial between 0 and 625D and between 625 and 625*2 plots to give a measure of internal replication within blocks, an analysis of covariance 3 years after fertiliser application was made for Blocks 1, 2, 4, 6, and 7. This analysis indicated that there is no strong evidence for the presence of treatment × site interactions. There was a weakly significant fertiliser effect (with a probability between 5 and 10%).

The measurement schedule and silvicultural treatment allowed two further pre-thinning analyses – one derived from the 0, 625, and 1250 treatments in Blocks 1, 2, 4, 6, and 7, and the other from the 0, 625, 1250, and 2500 treatments in Blocks 4, 6, and 7. The analysis of mean tree basal area (y) after covariance on initial mean tree basal area (x) showed that there was a significant fertiliser effect in both analyses. An approximate analysis of $(y\text{-}bx)^2$ where b is the covariance regression estimate (Cochran & Cox 1957) showed clearly significant linear and nonsignificant quadratic effects across the three rates and clearly significant linear and negative quadratic effects across the four rates.

Figure 2 shows the post-thinning basal area growth in Whangapoua averaged over the three blocks. An analysis of variance was made of basal area growth since thinning. Thinning to a fixed stocking plots already affected by fertiliser caused a significant fertiliser effect to occur in the initial basal areas. Final basal areas differed significantly. In Table 8 mean basal area growth is shown for each fertiliser treatment.

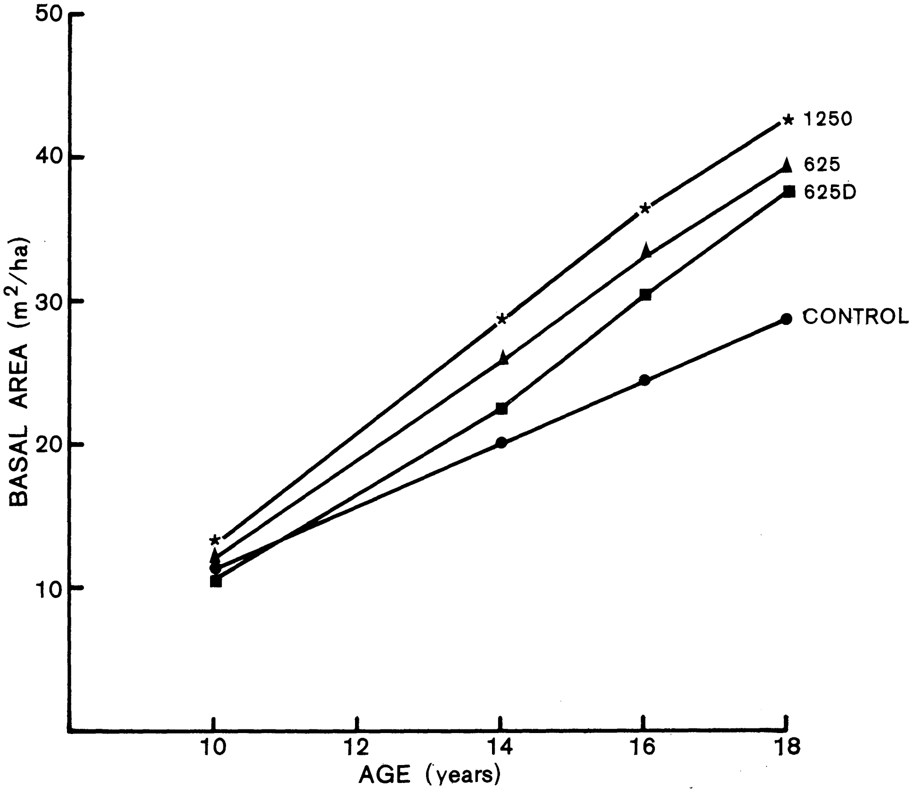

FIG. 2—Post-thinning basal area growth (m^2/ha) in Blocks 1-3, Whangapoua Forest

TABLE 8—Basal area increment (m^2/ha) after thinning (Blocks 1 to 3, tree ages 10–18)

Treatment	Unadjusted means
0	17.8_a
625D	27.6_b
625	27.8_b
625*2	32.5_b
625*4	30.1_b
1250	27.6_b
LSD	6.2

In order to increase the amount of information available about growth in the post-thinning period and to include information about rates of fertiliser and blocks not used in the analyses of covariance, a stepwise multiple regression was calculated of annual basal area increment against dummy variables for block, treatment, age, and basal area at the start of the increment period.

This regression surface (Appendix 1.3) indicated that large differences between blocks existed which appeared to be only weakly related to variation in other nutrient levels (*see* Table 4). Average basal area increments in the fertilised plots were significantly greater than in the control plots. Growth response to repeated small applications of fertiliser was no different from that to single large doses. The negative quadratic response surface across four single application rates identified in the analyses of covariance of Blocks 4, 6, and 7, may be general, i.e., the higher rates gave greater growth than the lower rate (625) but each increase brought a smaller increase in basal area.

CONCLUSIONS

Bringing together the evidence from the several partial analyses, it seems reasonable to form the following conclusions.

Height growth was affected by superphosphate fertiliser. Very significant height growth improvement was achieved on most sites with the lowest fertiliser rate (625) and little further improvement occurred with higher rates. Early height growth prior to fertiliser application on some phosphorus-deficient clays (e.g., Whangapoua and Glenbervie) was rapid and at a high predicted site index (Will 1965). On such sites fertiliser acted to maintain predicted site index while height growth in the control declined. At Riverhead early height growth was very poor. Fertiliser caused large increases in growth and site index. Differences between the fertilised and unfertilised plots are increasing with time. The controls appear to be developing into trees similar to those on which the first generation of phosphorus trials was conducted – sparse foliaged, stag headed, and very slow growing (Will 1965).

Basal area growth was greatly increased by superphosphate fertiliser. In the majority of the analyses, there is a negative quadratic component to increasing amounts of fertiliser. That is to say each successive increment in amount brings a smaller increment in growth.

Except with the highest rate applied at Riverhead (2500 kg/ha) the repeated application of small amounts of fertiliser gave growth which could not be distinguished statistically from single heavy doses. Since charges for fertiliser application are generally by the tonne-applied, repeated application would be cheaper in terms of interest charges and might help to even out some of the variability inherent in aerial topdressing (Ballard & Will 1971). Therefore the present policy of applying light dressings (currently when the need is indicated by foliage analyses) is endorsed by these results.

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APPENDIX 1.1

Stepwise multiple regression of annual height increments against fertiliser treatments.

Treatment	Coefficient	Standard error	t (121 d.f.)
625	+0.32	0.13	2.5
1250	+0.37	0.13	2.9
2500	+0.34	0.16	2.0
625*2	+0.31	0.13	2.4
625*4	+0.17	0.13	1.3
625D	—0.07	0.14	0.1
625 P%	+0.30	0.13	2.4

Control is dummy 0. Coefficients for block and tree age omitted. Multiple r = 0.50

APPENDIX 1.2

Regression of height increment against combined treatments.

Treatment	Coefficient	Standard error	t
Combined rates	+0.3398	0.083	4.1

Control is dummy 0. Coefficients for block and tree age omitted. Multiple r = 0.50

APPENDIX 1.3

Stepwise multiple regression of annual basal area increment against fertiliser treatments.

Treatment	Coefficient	Standard error	t (121 d.f.)
625	+0.60	0.29	2.1
1250	+0.74	0.29	2.6
2500	+1.02	0.40	2.5
625*2	+0.68	0.29	2.4
625*4	+0.54	0.30	1.8
625 P%	+0.94	0.30	3.2

Control is dummy 0. Coefficients for block and tree age omitted. Multiple r = 0.75