INFLUENCE OF NITROGEN AND PHOSPHORUS STRESSES ON THE GROWTH AND FORM OF RADIATA PINE

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ABSTRACT

Cuttings of two radiata pine (**Pinus radiata** D. Don) clones were grown for 6 years in lysimeters. Four soil conditions were used to study the effects of nutrition on tree growth and form — (1) subsoil, kept low in N; (2) subsoil, kept low in P; (3) normal proportions of topsoil and subsoil; and (4) double topsoil volume. The latter increased nutrient supplies — particularly of N.

The major effects of N or P stress on the trees were to restrict (1) stem diameter growth more than height growth and (2) branch growth more than stem growth. In contrast, trees with access to the additional nutrients (particularly N) in the double-topsoil lysimeters had larger diameters at breast height in relation to height, and larger branches producing considerably greater quantities of foliage each year; however, foliage retention time was decreased.

INTRODUCTION

The world forestry literature contains many references to restricted tree growth caused by inadequate levels of one or more nutrients in the soil.

Fertiliser trials in many countries have shown that, in many cases, the growth of both natural forests and plantations can be substantially and economically increased by the application of fertilisers (Tamm, 1968); this has led to an increasing world-wide use of fertilisers in forests (Baule, 1973).

Growth assessments have usually been based on measurements of height and diameter at breast height (d.b.h.) and the use of standard volume tables. There are few published reports of studies into possible changes in stem form resulting from the application of fertilisers. In high-production radiata pine (*Pinus radiata* D. Don) stands in the central North Island of New Zealand Woollons and Will (1975) found no height responses to applications of N fertiliser but a concentration of increased diameter growth in the upper stem giving a positive change in stem form. In the Nelson district of the South Island, New Zealand, Mead (1974; 1976) has also reported only slight height increases but considerable diameter responses to N plus P fertilisers, particularly in the upper stems of radiata pine. Miller and Cooper (1973), however, found no change in stem form when Corsican pine (*Pinus nigra* ssp. *laricio* (Poiret) Maire) responded to N.

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In their assessments of fertiliser responses many research workers have found increased foliage mass — in terms of increased needle length and weight — and photosynthetic rate (e.g., Wells, 1970; Keay *et al.,* 1968). Baker *et al.* (1974) and Cromer and Hansen (1972) have measured increases in stem dry matter compared to dry matter in branches (including foliage) for loblolly pine (*Pinus taeda* L.) and eucalypts respectively.

In 1967 a set of lysimeters was constructed in the grounds of FRI (Gifford, 1970). The major objective was to measure the effects of soil moisture stress on the seasonal growth patterns of radiata pine cuttings from three different clones originally randomly chosen as seedlings from routinely collected seed (Jackson *et al.,* 1976). Provision was also made to study the effects of N and P levels on growth of two of the clones (Clones 451 and 460). Some preliminary results on tree growth as influenced by N supply have been reported (Will, 1971). The present paper gives results of the full study through to and including the harvesting of the trees 6 years after they were planted.

METHODS

Most lysimeters consisted of 2.7-m^3 containers set in the ground and filled with the sandy loam pumice soil occurring on the site. "Normal Topsoil" units were filled with subsoil and topsoil so as to give the best possible reconstruction of the normal soil profile. Levels of available N and P in this soil are considered near optimal for tree growth. "Low-N", "low-P", and "low-NP" units were filled with texturally similar pumice subsoil from a nearby excavation. However the "Double Topsoil" units were constructed so as to give twice the topsoil surface area (3.0 m^2 compared to 1.5 m^2). They had walls which extended to a depth of only 1 m but no floors, and this gave unrestricted root access to the subsoil below.

For each clone there were 3 low-N lysimeter units, 3 low-P units, 1 low-NP unit, 1 Normal Topsoil unit, and 2 Double Topsoil units. The differences in numbers for each treatment were dictated by the number of units surplus to the needs of the major soil moisture study. In the winter (July) of 1967 two 27-month-old rooted cuttings were planted in each unit. Fertiliser applications (surface broadcast) began in January 1968 to correct all but the designated deficiency in the low-N and low-P units:

Low-N units — 10 g urea (46% N) in January 1968 as a starter; 100 g of superphosphate (10% P) in January and October 1968 and 250 g each succeeding spring;
Low-P units — 30 g of urea in January and October 1968 and 100 g each succeeding spring;
Low-NP units — no fertiliser until age 3 years when they were converted to plus-NP treatments and received both urea and superphosphate.

Heights and diameters (20 cm above ground level) were measured on all trees at regular intervals — every 10 days for most of the 6 years.

At the end of the first year one tree was removed from each unit; the tree with height nearest the mean for all trees of the clone was left.

At intervals during the 6 years, analyses of current foliage were carried out, crown diameter and branch diameters were measured, and photographs were taken.

The experiment was terminated after 6 years and one tree from each treatment (except low-NP) for each clone was destructively sampled. A mean (height and diameter) tree was selected but there was little variation between trees of the same clone and treatment.

The following measurements were made:—

(1) Height to each branch cluster;

(2) Stem diameters above and below each branch cluster but clear of nodal swelling;

(3) Lengths and basal diameters of all branches;

(4) Each branch cluster was separated into its component parts — first- second-, and third-year foliage, immature shoots, branches, and cones. Each component was weighted, and then the full amount or a sub-sample was oven dried;

(5) After foliage and cones were removed the main stem was cut into six sections at points corresponding to previous midwinters' terminal heights. Stem sections were weighed before a knot-free disc was taken for oven drying;

(6) Each tree was photographed from an adjacent meteorological tower. The stem was placed on a sloping platform marked with 1-m square grid lines: the longest branch from each cluster was then placed to the left of its node and a mean-length branch to the right;

(7) After the trees had been felled, the lysimeter boxes were lifted out of the ground and the framework dismantled. The roots were shaken loose from the soil block using a hydraulic digger and were then collected by raking through the soil and cutting those still attached to the stump. Stump height was 20 cm above ground-level — the reference point for measurements throughout the trial.

Three size-classes of roots were recognised:—

A. 5-10 mm diameter

B. 10-20 mm diameter

C. >20 mm diameter

All roots were cut into 10-20 cm lengths and air dried, and a 10% sub-sample was oven dried. Root bark was discarded because of the decay which had occurred during the several months between felling and root harvesting. For the same reason roots <5 mm diameter were not harvested. The stump was weighed and sawn into quarters, and one-quarter was stripped of bark before oven drying and weighing of both wood and bark.

RESULTS AND DISCUSSION

Height and Diameter Growth

There was a marked difference between the seasonal patterns of height growth in Clone 451 trees and those of Clone 460 (Fig. 1). Clone 460 trees showed a faster rate of height growth in the spring of each year, followed by a distinct period of slower growth in the late summer to autumn. The more even rate of growth in Clone 451 was associated with the formation of a greater number of branch clusters per year (see Table 1) and continuous dominance; in contrast, Clone 460 was subject to retarded leader (see *Measurements at Harvest*).

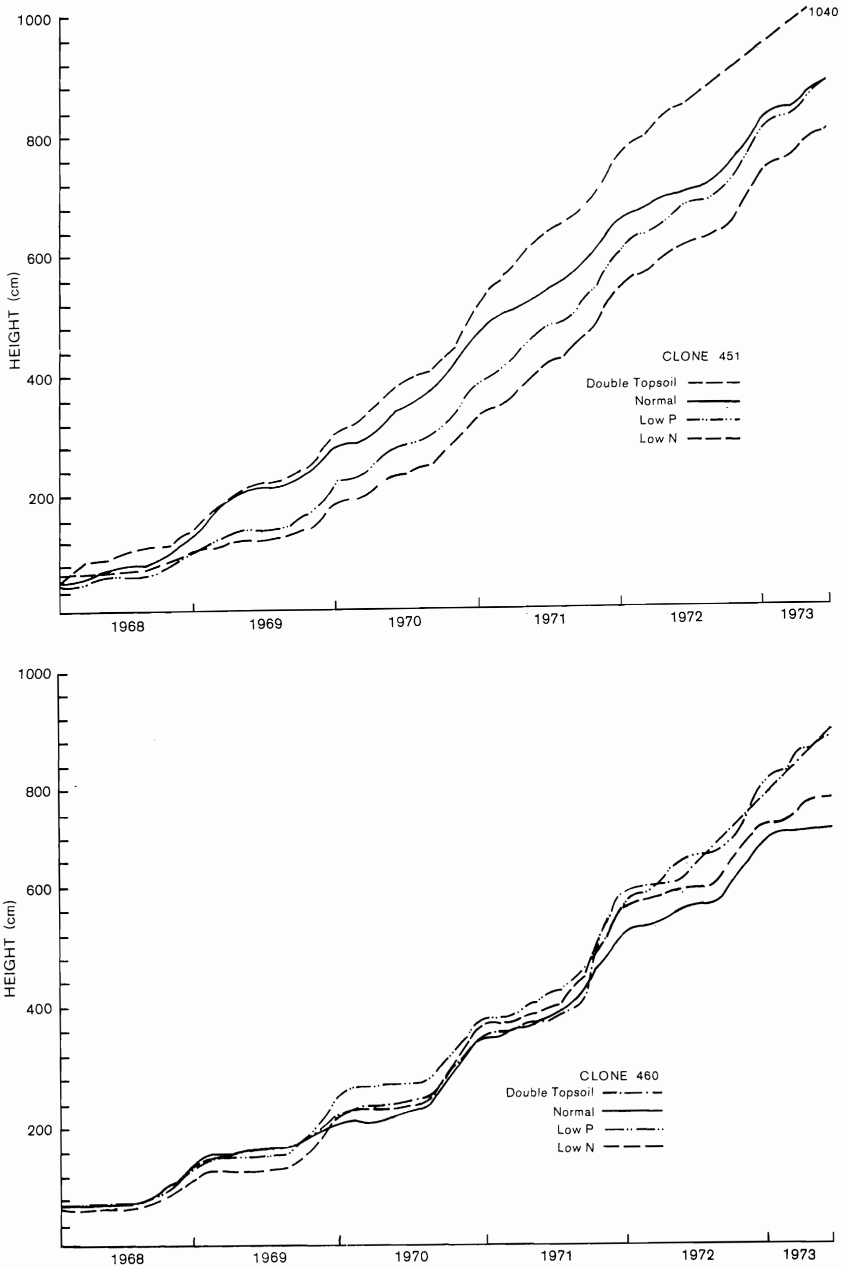

FIG. 1—Tree height growth 1968-73.

TABLE 1—Crown characteristics of harvested trees

	Height (m)	d.b.h. (cm)	Ht / diam.	No. of branch clusters	Mean no. of branches per cluster	Branches: Mean length (m)	Branches: Mean basal diam. (cm)
Clone 451							
Low N	8.1	11.5	70	21	5.5	0.98	1.46
Low P	9.1	12.8	71	23	5.5	1.19	2.09
Normal Topsoil	8.7	16.2	54	23	5.5	1.41	2.44
Double Topsoil	10.4	22.4	46	23	6.5	1.97	3.50
Clone 460							
Low N	7.4	9.8	76	9	8.8	0.96	2.50
Low P	8.6	13.4	64	13	7.6	1.48	2.68
Normal Topsoil	7.0	12.0	58	13	5.4	1.59	2.8
Double Topsoil	8.7	16.4	53	13	6.4	1.94	3.63

Although low levels of N or P had only a slight effect on height growth, they resulted in appreciably lower rates of diameter growth (Fig. 2). As trees were watered during periods of drought, the greater growth in the Double Topsoil trees suggests a more favourable nutrient supply because of the larger volume of topsoil available to them. Foliage analyses (Table 2) confirmed this, particularly with respect to N. It should be noted that the low-N and low-P trees were deficient in those nutrients but all other nutrients were in adequate supply in all treatments (Will, 1966), except Mg which was marginal.

Branch and Foliage Growth

Low levels of N and/or P retarded branch growth more than stem growth resulting in a narrow crown with marked leader dominance by age 3½ years (Fig. 3). Branch growth of mid-crown clusters during the preceeding spring, and needle lengths are given in Table 3. These data illustrate the more vigorous branch growth that occurred in the Normal Topsoil and Double Topsoil trees.

As there was such a marked difference in form between the low-N, low-P, and low-NP trees on the one hand and the Normal Topsoil and (particularly) the Double Topsoil trees on the other, it was decided to abandon the low-NP units as such and convert them to plus-NP. This was to confirm that the growth pattern in the low-N, low-P, and low-NP units was truly a nutrient effect and not the result of some other property of the subsoil used.

Urea and superphosphate were applied and by age 4 years there was a visible

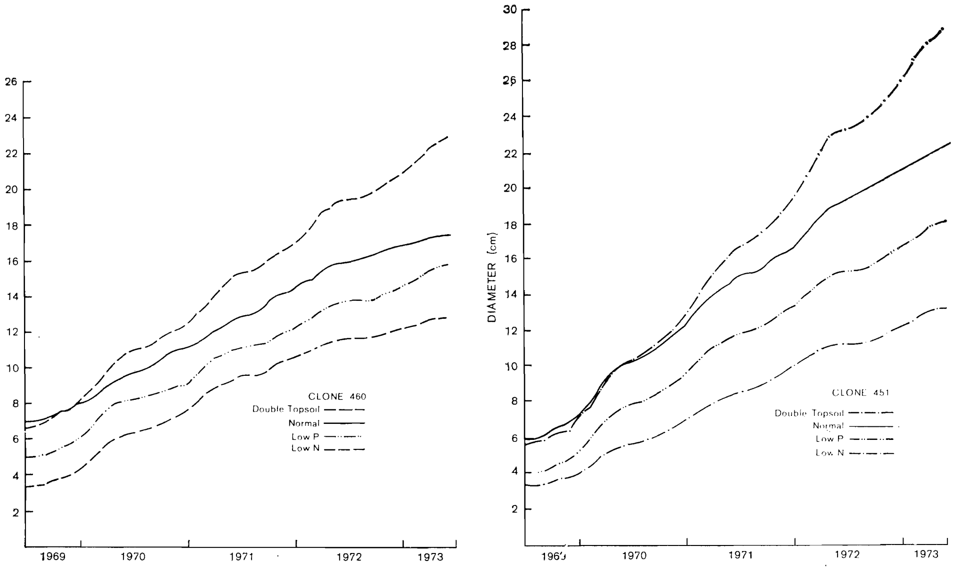

FIG. 2—Tree stump diameter growth 1969-73.

TABLE 2—Mean foliage nutrient concentrations (23/1/69) for four nutrient treatments

Treatment	N%	P%	K%	Ca%	Mg%
Low N	1.26	0.14	0.91	0.30	0.08
Low P	1.50	0.09	0.92	0.23	0.07
Normal Topsoil	1.47	0.13	1.07	0.16	0.07
Double Topsoil	1.63	0.14	0.87	0.25	0.10

difference in the now plus-NP trees—branch habit had become more like that of the trees in the Normal Topsoil than of the low-N and low-P trees. By age 5 years the major clusters of branches formed the previous spring had the following lengths and diameters:—

	Branch length (m)	Branch basal diameter (cm)
Normal Topsoil	2.45	3.3
Plus-NP	2.35	3.3
Low-N	1.77	2.2
Low-P	2.04	2.9

In appearance also the plus-NP trees had become distinctly different from the low-N and low-P trees but indistinguishable from those in Normal Topsoil. This confirmed that the effects observed in the low-N and low-P trees were in fact due to nutrition.

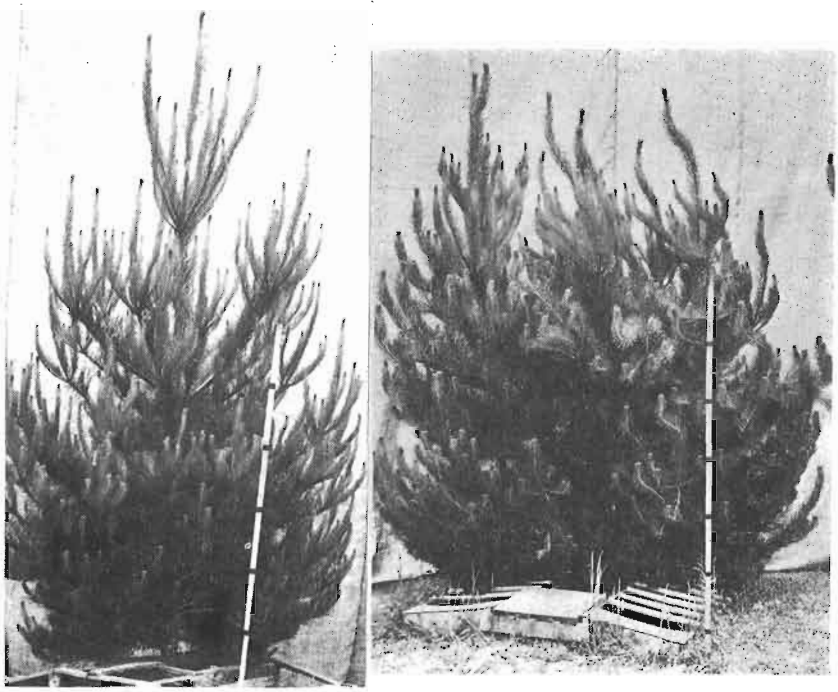

FIG. 3—Comparison of low-N (left) and Double Topsoil (right) trees, Clone 460 at age 3½ years.

TABLE 3—Spring 1970 shoot extension (cm) on ends of primary branches initiated 2 and 3 years earlier on Clone 460 trees, and lengths of mature needles (cm)

Treatment	Age of branch 2 years	Age of branch 3 years	Needle lengths
Low N	37	32	7.5
Low P	41	34	9.8
Normal Topsoil	57	40	15.0
Double Topsoil	79	54	>15.0*

* Visual comparison with Normal Topsoil.

An expected increased needle retention associated with trees under least nutrient stress did not occur (the situation at time of harvest is illustrated in Table 4 and Fig. 4). For these the volume of each season's new foliage was great enough to almost completely shade the previous year's foliage, thus hastening the shedding of older foliage. On the low-N and low-P trees, sustained height growth, shorter branches, and smaller needles doubtless combined to produce a minimum of internal shading.

TABLE 4—Summary of o.d. weights (kg) of the crown and stem components of the eight representative trees harvested at the end of the experiment

	Immature shoots	Foliage				Cones	Branches*	Total crown**	Total main stem	Ratio wood : bark (stem)	Ratio stem : total crown
		1 year	2 year	3 year	Total						
Clone 451											
Low N	0.16	1.64	1.80	0.69	4.13	0.91	4.60	9.80	12.45	7.2	1.27
Low P	0.65	4.36	3.39	2.04	9.80	1.64	16.92	29.00	24.07	7.4	0.83
Normal Topsoil	0.61	3.88	5.83	3.29	13.00	4.12	22.41	40.14	32.10	7.2	0.80
Double Topsoil	3.40	16.76	12.57	2.90	32.23	5.05	67.89	108.57	62.89	10.0	0.58
Clone 460											
Low N	0.10	1.48	1.41	0.23	3.12	0.02	6.59	9.83	9.55	5.2	0.97
Low P	0.62	5.38	2.23	0.12	7.73	0.01	16.33	24.69	19.74	6.0	0.80
Normal Topsoil	0.25	2.57	4.33	1.14	8.04	0.00	24.36	32.65	14.37	4.7	0.44
Double Topsoil	1.58	11.60	5.95	0.00	17.55	0.00	42.79	61.92	36.64	6.1	0.59

* Branches = Branch stems minus foliage, etc.

** Total Crown = Branches plus foliage, etc.

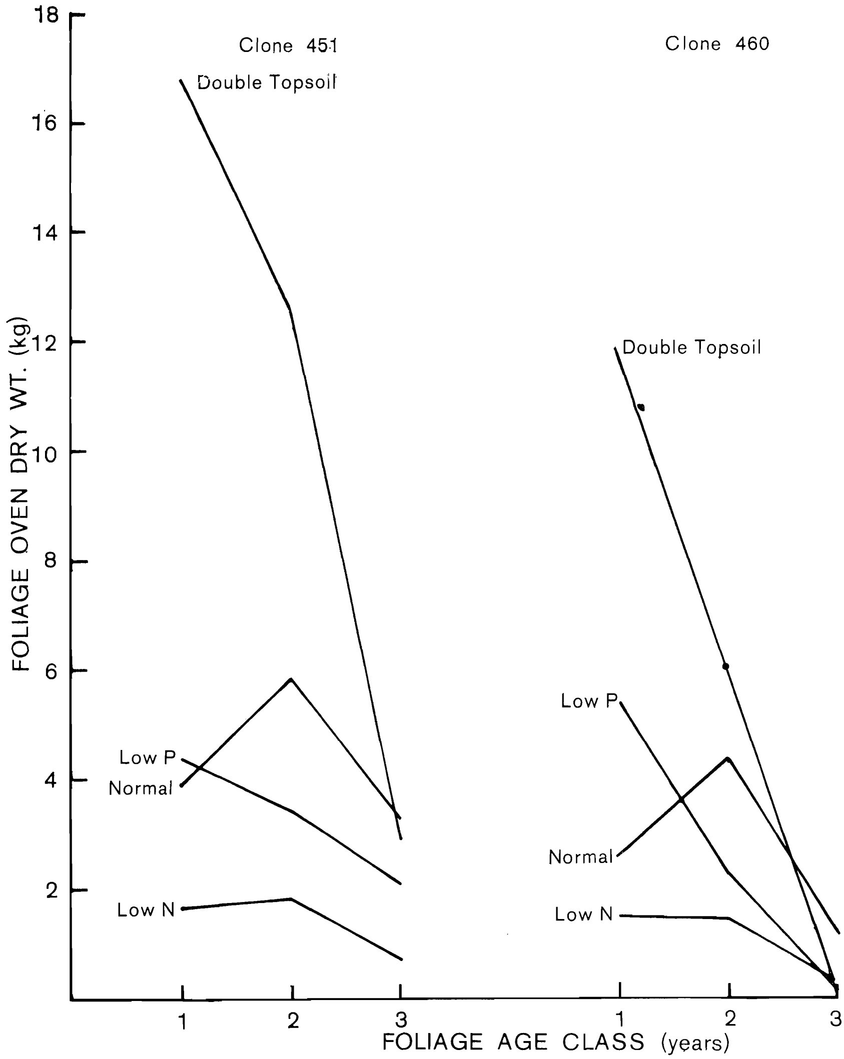

FIG. 4—Foliage distribution by age class at harvest.

Distribution of Wood Production

Relatively normal height growth but considerably reduced diameter and branch growth in the low-N and low-P treatments (Table 4) clearly combined to have a marked effect on the amount of wood produced and its distribution within the tree. The distribution of the volume of wood within and between low-P, Normal Topsoil, and Double Topsoil trees of Clone 460, $3\frac{1}{2}$ years after the experiment began, is illustrated in Fig. 5. The areas representing stem volumes are accurate but representing branch volumes as triangles certainly results in an under-estimation.

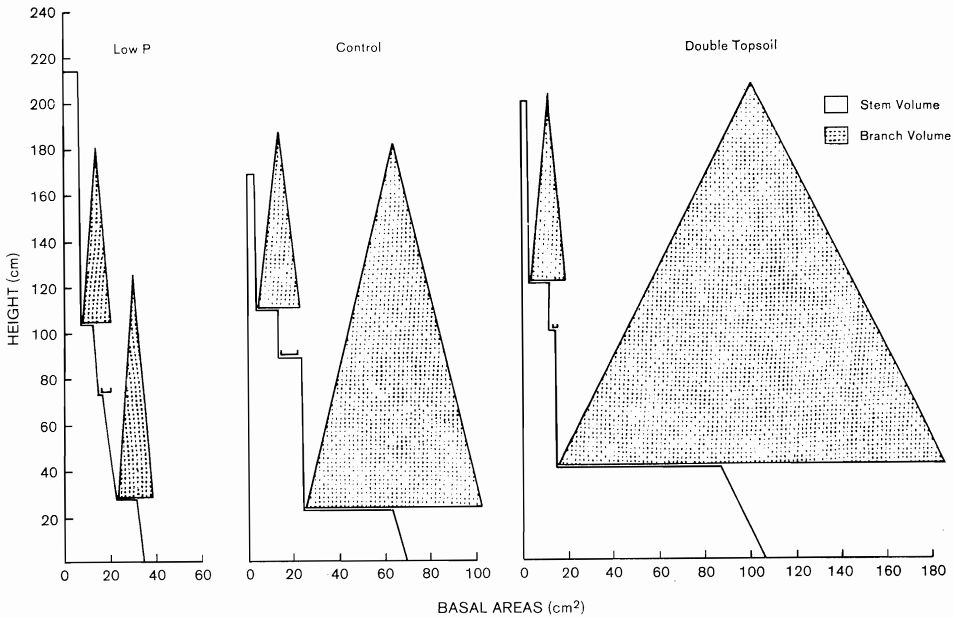

FIG. 5—Comparison of stem and branch growth of three trees of Clone 460, 3½ years after treatments.

Male Cone Production

During the last years of the experiment the smaller total branch growth on the low-N and low-P trees was associated with reduced vigour of the current growth on the branches in the lower part of the crown. This state developed even though there was no competition for light from neighbouring trees. Along with this lack of vigour was an absence of male cone production. On the low-N trees in particular, male cones were restricted to the upper few branch clusters while, in contrast, the Double Topsoil trees produced male cones on branches within 1 m of the ground.

Measurements at Harvest

Crown form:

Tree heights, total numbers of branch clusters, and mean branch lengths and basal diameters are given in Table 1. Reconstructed tree crowns showing maximum and mean length branches from each cluster for Clone 451 are shown in Fig. 6.

It is obvious that low-N and low-P trees had appreciably less branch growth than but similar height growth to the Normal Topsoil and Double Topsoil trees. This confirms earlier measurements. Except for slightly lower numbers on the low-N trees, the number of branch clusters produced was constant.

Apical dominance in Clone 451 was not affected by any treatment; however, in Clone 460 in the first two growing seasons both the Normal Topsoil and Double Topsoil trees suffered severe loss of apical dominance, or "retarded leader" as it is

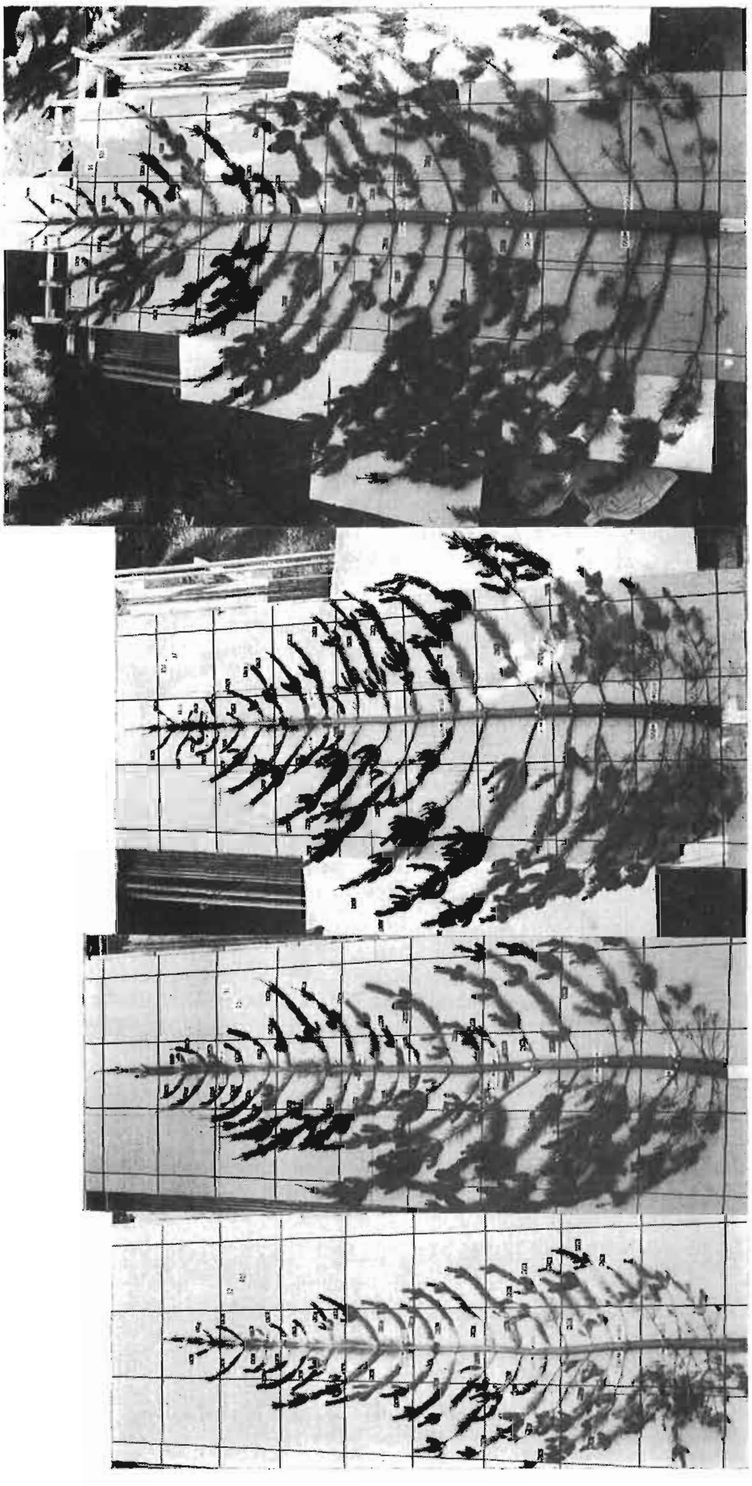

FIG. 6—Comparison of stem and branch growth in Clone 451 trees after harvest. From left to right: low N; low P; normal topsoil; double topsoil.

commonly called. This condition is very common in plantations of radiata pine in New Zealand and results from autumn growth of the terminal cluster of branch buds while the leader bud remains dormant (Will, 1971). The leader shoot of Normal Topsoil trees regained dominance each summer but in the Double Topsoil trees apical dominance was not regained and the original main axis persisted as only a small suppressed "branch". This loss of apical dominance presented a problem in distinguishing between branches and main stem at this point. This was resolved by ignoring the original leader from the point at which it became suppressed and regarding the largest branch from the 1968 autumn-winter terminal cluster as the new leader.

Stem form:

There was a consistent decrease in the ratio of total height to d.b.h. as the nutrient status of the trees increased (Fig. 6 & Table 1). Clone 460 with its lower number of branch clusters and larger-diameter branches (Table 1) showed much greater reductions in cross-sectional area from below to above each cluster.

Dry matter production:

Details of total dry weights of immature shoots, foliage, cones, and branches (Table 4) confirm differences in branch growth shown in Fig. 6 and Table 1. Few or no cones were present on Clone 460 trees but in Clone 451 the total weight of cones present increased with nutrient status and crown weight.

Stem dry-weights — wood plus bark — are given in Table 4 together with wood : bark and total-stem : total-crown ratios. Full details of sectional measurements are available (Hodgkiss, 1974) but the tree means show the consistently higher wood : bark and stem : crown ratios for Clone 451. Within each tree, wood : bark ratios were lowest in the top sections of the tree, increased to about double just below mid-height, and fell to an intermediate value in the basal two sections.

Root and stump weights are given in Table 5. Although roots less than 5 mm in diameter and root bark were not harvested, the recorded total weights of roots plus stump are unlikely to be less than actual values by more than 10-15%; this is suggested by the decreasing total weights of roots with decreasing root size and the wood : bark ratio of the stump. The point of division (20 cm above ground level) tends to counteract the incomplete harvesting of all roots so the shoot : root ratios in Table 5 can be regarded as reasonably accurate.

In radiata pine seedlings, low levels of N supply reduce shoot growth more than root growth resulting in low shoot : root ratios (Will, 1961). There is some indication, particularly for Clone 460, that the same is true for 8-year-old cuttings. On the other hand it seems that a low level of P suppresses root growth in relation to shoot growth.

VALIDITY OF RESULTS

The value of this study depends on the validity of the results provided by lysimeters under the particular conditions. Lysimeters have been used for nearly two centuries to study details of soil-plant relationships but various difficulties have been encountered, particularly with trees. This led Patric (1961) to state "The conclusion is inescapable that lysimeters are a poor place for raising trees. Is there then a place for lysimeters in forestry research? Undoubtedly there is, but data from such experiments must be

TABLE 5—Estimated dry weights (kg) for roots and stumps, and shoot : root ratios

	Root size (mm)			Stump		Total	Shoot : root
	5-10	10-20	>20	Wood	Bark		
Clone 451							
Low N	0.17	0.39	1.14	2.51	0.39	4.60	4.8
Low P	0.42	0.71	2.04	4.06	0.85	8.08	6.6
Normal Topsoil	0.51	1.18	3.52	8.08	1.54	14.83	4.9
Double Topsoil	0.45	1.41	13.99	12.61	1.68	30.14	5.7
Clone 460							
Low N	0.47	0.53	0.47	2.33	0.42	4.22	4.6
Low P	0.64	0.78	0.85	3.66	0.68	6.61	6.7
Normal Topsoil	0.68	0.88	1.89	4.13	0.92	8.50	5.5
Double Topsoil	0.88	1.46	5.68	6.89	0.92	15.83	6.2

treated with great caution. . . . Lysimeter results derived from trees will necessarily be based upon plants smaller and less vigorous than those expected to survive under natural competition".

The growth of trees — cuttings from two clones — in the experiment reported in this paper does not support Patric's conclusions. Sweet and Wells (1974) reported that radiata pine cuttings on a high-quality site in northern Kaingaroa Forest grew to heights of up to 7.5 m in 5 years. Heights of up to 10.4 m in the 6 years of this study strongly support the contention that the soil and container size and construction used allowed essentially normal growth. Though diameter growth was certainly sub-optimal in the closed lysimeters, it was certainly within a range which would be regarded as normal. In addition, radiata pine seedlings planted between the rows of lysimeter units did not make greater height growth than the cuttings in the lysimeters. The results of this study, then, can be applied to tree growth in plantations with some confidence.

CONCLUSIONS

When compared with trees grown in soil of adequate fertility, those grown in soils low in N or P show:

(1) Little difference in height growth;

(2) A considerable reduction in diameter growth;

(3) A marked decrease in branch size resulting in narrow crowns and a higher proportion of the above-ground mass in the stem.

Giving a tree access to a greater volume of topsoil and thus increasing its nutrient uptake, particularly of N (as shown by foliage analyses), reversed the effects in (2) and (3) — the increase in branch vigour led to malformation in one clone.

Nutrition had no detectable effect on the ratio of wood : bark in the stem which was usually at a maximum just below mid-height. Increased nutrition markedly increased annual foliage production but not the number of years it was retained on the tree.

These results confirm that the light branching and good stem form of radiata pine in forests on coastal sands and in the Nelson district is rightly attributed to known N deficiencies. They also provide an explanation for the very rough form and high degree of malformation found in plantations on very fertile sites.

The good stem form of both clones in deficient soils but the greater degree of deterioration (malformation, etc.) in Clone 460 under more fertile conditions provides evidence to support the contention that progenies should be tested on one or more soils at least as fertile (particularly in N) as any existing in forests to be planted.

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