SOIL SOLUTION PHOSPHORUS AND *EUCALYPTUS NITENS* ROOTS IN NP-TREATED MICROSITES IN HIGHLY PHOSPHORUS-FIXING SOIL

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ABSTRACT

Application of phosphorus (P) fertiliser to a microsite about 20 cm from each seedling soon after planting is a common practice in eucalypt plantations. To improve our understanding of phosphorus availability to *Eucalyptus nitens* (Deane et Maiden) Maiden plantations grown in a highly phosphorus-fixing soil, we determined the effects of spade-slit placement of fertiliser on (i) concentrations of phosphorus in soil solution (P_l) around these microsites at 2, 6, 18, and 42 months after fertiliser application, and on (ii) fine root distribution at 18 months. Within 5 mm of the fertiliser, values of P_l decreased from at least 1000 μM soon after planting, to 100 μM at both 18 and 42 months. By 18 months, fertiliser application had increased P_l laterally up to 50 mm and vertically to a depth of 300 mm, despite the high phosphorus-fixing capacity of the soil (i.e., indicated by 472 μg P/g soil required to achieve 0.2 μg/ml in solution). Elevated phosphorus concentrations with depth were associated with high root-length densities (29×10^4 m/m^3), but enhanced root growth may have also resulted from higher availability of nitrogen (N) in these fertile microsites. We concluded that microsite application of fertiliser was an effective way of maintaining high phosphorus availability to some root surfaces in this soil for at least 42 months after treatment. This method may alleviate the need for additional applications of phosphorus fertiliser later in the life of the crop.

Keywords: soil solution; phosphorus; phosphate sorption; buffering; fertiliser; roots; *Eucalyptus nitens*.

INTRODUCTION

Eucalyptus nitens is an important hardwood plantation species in frost-prone, high rainfall, temperate regions of Australia. Soon after planting in Australia and elsewhere, phosphorus fertilisers either alone or with other nutrients are commonly applied close to the seedling in spots, slots, or strips of various sizes and configurations (Attiwill & Adams 1996). These methods of application lead to a localised increase in nutrient availability, i.e., a fertile

microsite. Compared to broadcast applications, microsite placement of phosphorus fertiliser in highly phosphorus-fixing soils enhances phosphorus supply and uptake to a variety of crops (Barber 1995; Moody *et al.* 1995).

Plants require a minimal concentration of orthophosphate-phosphorus in solution to optimise phosphorus uptake and growth (Asher & Loneragan 1967). In soils that have a high capacity to buffer these concentrations (conferred by their high phosphorus-fixing characteristics), the concentration of orthophosphate-phosphorus in soil solution (P_I) has been used as an indicator of phosphorus status for some agricultural crops. For example, non-limiting concentrations of P_I range from 0.2 μM for cassava (*Manihot esculenta*) to 9.7 μM for lettuce (*Lactuca sativa*), while a range of other agricultural crops (Fox 1981) and *Pinus radiata* D.Don (a common forest plantation species—Skinner & Attiwill 1981) have intermediate requirements. The comparable value for any eucalypt has not yet been determined, but because eucalypts have evolved in an environment of low phosphorus availability they have efficient mechanisms of phosphorus acquisition and utilisation (Grove *et al.* 1996).

To guide future management of phosphorus in these soils we seek an improved understanding of phosphorus supply and uptake in these plantations, similar to that described for some species by Nye & Tinker (1977) and Barber (1995). One constraint has been our limited knowledge of the spatial and temporal variation in P_I and root growth in relation to microsite placement of fertiliser.

The objectives of the research described here were to describe the spatial and temporal variation in P_I around treated microsites in a highly phosphorus-fixing soil, and describe the effect of fertiliser application on the lateral and vertical distribution of root-length density.

MATERIALS AND METHODS

Sites

Sites chosen for the study were in north-western Tasmania at 500–600 m elevation and about 50 km south of Burnie, i.e., about 145°45′ east and 41°15′ south. The region receives about 2000 mm precipitation annually, which is distributed evenly throughout the year, and has a cool temperate climate with snow falls and frosts in winter. Soils at all sites had a brown clay-loam texture in the surface 10 cm that graded to a red-brown light or medium clay at 40 cm and deeper, were moderately well structured, and were classified as Ferrosols (Isbell 1996) and Lithic Eutrudoxs (Soil Survey Staff 1990). All profiles contained rocks of weathered basalt (parent material) and were impenetrable with an auger beyond 80–120 cm depth. The profile was typical of dark brown clayey soils in the region derived from basalt, which in the top 100 mm have a $pH_{1:5\ water}$ 5.8, total P 1094 mg/kg, total N 4.3 g/kg, organic C 51 g/kg, and bulk density 0.5 g/cm^3 (Grant *et al.* 1995, pp.176–177).

All sites supported a mixture of eucalypt and rainforest species which were harvested before site preparation in March-June of the year of planting. The soil was ripped to about 60 cm depth and mound ploughed in rows about 3.5 m apart, similarly to mounding described by Attiwill *et al.* (1985). Seedlings of *E. nitens* were planted at 2.6-m intervals on the tops of mounds. After planting, all sites were kept weed-free by the application of herbicides.

An existing experiment and two operational plantations were sampled during April-July 1995 at approximate ages 6 months (Middlesex site), 18 months (Rabbit Plain site), or 42

months (Wages Road site). The 6-month site contained an experiment designed to examine the effect of timing of the application of phosphorus fertiliser on tree growth (data not presented). In the two timing treatments sampled, 100 g diammonium phosphate (DAP; N:P ratio 18:20) had been placed in a spade-slit (approximately 5–15 cm deep) on both sides of each seedling about 20 cm from the planting position either 2 or 6 months prior to sampling. These two timing treatments were replicated four times in plots containing 25 trees each. The 18- and 42-month sites were operational plantations that had received 100 g DAP in a spade slit on one side of each tree within 1 month of planting. Hence, fertiliser-treated microsites at all sites each received approximately 20 g P (elemental).

Phosphorus Sorption

At the 6-month site, 10 cores of soil 0–10 cm deep and 5 cm diameter were taken from one plot in each replicate (four plots total) in the untreated areas of the tops of mounds. These samples were bulked, air-dried, mixed, and sieved. The phosphorus sorption characteristics of the <2-mm fraction of soil were determined by equilibrating in triplicate 5 g soil with 50 ml solution containing either 0, 1.6, 6.4, 26, 104, 416, or 1664 mM P as KH_2PO_4 and 2 mM $CaCl_2$ adjusted with HCl to pH 4.6, a typical pH in soil solution in these plantations. Samples were shaken at room temperature (c. 22°C) for 17 h. Shaken solutions and blanks were filtered through Whatman No. 42 filter paper and analysed for P_I (soluble molybdate-reactive phosphorus; Rayment & Higginson 1992). The concentration of phosphorus sorbed to the solid phase was expressed as a function of the concentration of phosphorus in the equilibrated solution using a Freundlich function modified to include a y-intercept (Sibbesen 1981). The sorption function was fitted by non-linear regression using Statgraphics®.

Fertiliser Effects

At the 6-month-old site, soil was sampled near eight trees, one in each replicate of the 2-month and 6-month treatments. Careful scraping of the surface 0–50 mm soil revealed the top of the fertiliser, which had been placed in a spade-slit and was in a vertical planar orientation (approximately 15 mm thick, 70 mm wide, and 100 mm deep) aligned along the cultivated row. By careful excavation using spades, trowels, spatulas, and brushes, at least several grams of soil were collected from each zone 0–5, 5–15, 15–30, 30–60, 80–100, 160–200 mm, both horizontally away from the plane of fertiliser and vertically underneath the fertiliser starting 15 cm below the soil surface (no obvious remains of fertiliser granules were included in the soil samples). A sample of the fertiliser remains was sampled separately.

Values of P_I were measured using a paste method (Smethurst *et al.* 1997). This method involved the equilibration of fresh soil samples with deionised water for 1 h at room temperature, followed by separation of the liquid by centrifugation and filtering. For most samples, a solution:soil ratio of less than 10 was used to minimise variability, but for some small samples a ratio of 30 was needed to provide enough liquid for analysis. These ratios were within the limits expected to provide accurate estimates of P_I without needing to correct for dilution effects (Grinsted *et al.* 1982; Smethurst *et al.* 1997).

At the 18-month site, soil was collected from horizontal and vertical transects on the fertiliser-treated and untreated sides of four trees. On horizontal transects through the fertiliser spots, and in equivalent untreated positions on the opposite side of each tree, soil

cores (50 mm long, 19 mm diameter) were collected from distances of –100, –50, 0, 50, 100, 150, and 300 mm in relation to the fertiliser spot and away from the tree. Duplicate cores were taken at each lateral distance for measurements of P_I and root-length density (L_v, Tennant 1975), except P_I was not measured at the –50, 50, and 150 mm positions. On vertical transects through the fertiliser spots, and in equivalent untreated positions on the opposite side of each tree, soil was sampled at 50-mm intervals to 300 mm depth and below that at 100-mm intervals to 700 mm depth. Alternate vertical cores were retained for measurements of P_I or L_v. At the 42-month-old site, soil was collected only from the 0–5 mm zone horizontally beside each of four fertiliser-treated microsites.

Fertiliser effects on P_I (or L_v) *v.* distances from the fertiliser were considered by fitting polynomial functions to individual observations using Sigmaplot®. These functions (usually 3° provided the best fit) were considered significantly different where the 95% confidence intervals did not overlap. Individual pairs of means were compared by t-test.

RESULTS

Phosphorus Sorption

Some samples with concentrations of P_I in excess of 20 mM were coloured and they were therefore excluded due to potentially inaccurate estimates of concentrations. The remaining observations, which formed a curve that did not reach a maximum in the range of concentrations examined, was well described by a modified Freundlich function:

$$y = 106.0x^{1/3.325} - 8.004 \qquad (R^2 = 0.998,\ n = 24) \qquad [1]$$

where y is phosphorus sorbed (μmol/g) relative to that present in soil without added phosphorus, and x is the concentration of phosphorus in solution (μmol/ml) after shaking.

Soil Solution Phosphorus at 2–42 Months

Values of P_I in solution were very high (8000 μM) in the fertiliser 2 months after fertiliser application, but decreased significantly (t test, $p < 0.05$) to about 1000 μM by 6 months (Fig. 1). At 15–30 mm laterally, concentrations were 20–100 μM at both 2 and 6 months. Values of P_I had not been influenced by fertiliser application beyond 30 mm laterally by 2 months. By 6 months, concentrations at 30–60 mm increased to 20 μM, but this increase was significant only at $p = 0.17$. The 95% confidence bands of the relationships between lateral distance and phosphorus concentration for the two periods after fertiliser application overlapped for all lateral distances.

In contrast to the slow movement of phosphorus laterally, elevated values of P_I were evident to 60 mm below the fertiliser by 2 months, and had declined in this zone to more intermediate values after 6 months (Fig. 2). Values of P_I 0–5 mm adjacent to the fertiliser decreased from about 1000 μM at 2 months to 400 μM at 6 months, and were 100 μM at the 18-month and 42-month sites (Fig. 3).

Solution Phosphorus and Roots at 18 Months

By 18 months, elevated concentrations of P_I had not extended to 100 mm laterally from the fertiliser-treated microsite (Fig. 4), but were evident to a depth of 300 mm (Fig. 5). Coincident with elevated concentrations of phosphorus adjacent to the fertiliser-treated

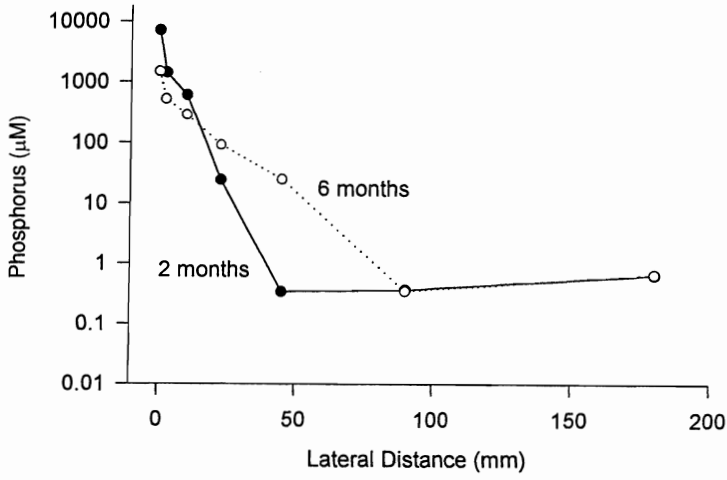

FIG. 1–Concentrations of phosphorus in soil solution *v.* lateral distance from fertiliser-treated microsites 2 months (●) and 6 months (○) after application. Points are shown at the centre of the measurement zone. Confidence intervals (95%) for both periods overlapped throughout the range of lateral distances.

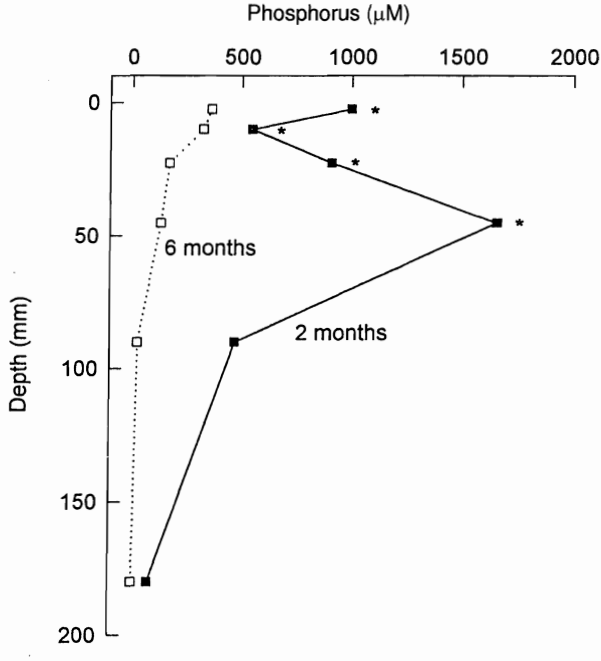

FIG. 2–Concentrations of phosphorus in soil solution *v.* depth 2 months (■) and 6 months (□) after fertiliser application. Depth at 0 cm is equivalent to a depth of 15 cm below the soil surface. Concentrations at 2 months were significantly greater (*, $p < 0.05$) than at 6 months for all depths down to and including the 30–60 mm zone. Points are shown at the centre of the measurement zone.

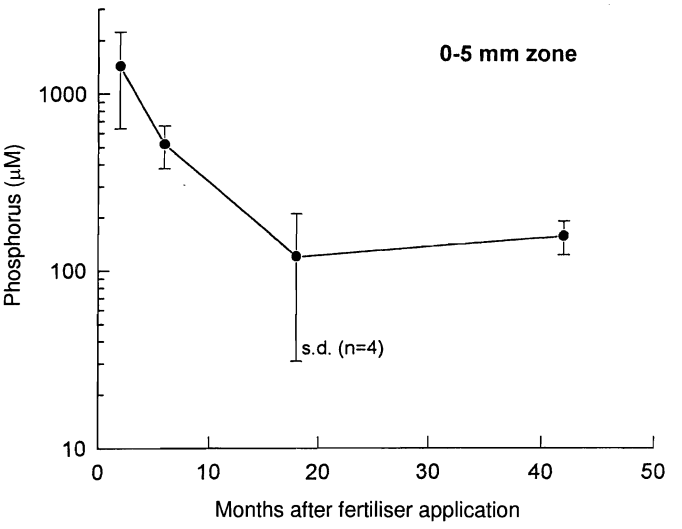

FIG. 3–Concentrations of phosphorus in soil solution in the 0–5 mm zone adjacent to fertiliser-treated microsites between 2 and 42 months after application. Bars are standard deviation (n = 4).

microsite and with depth were increases in L_v up to 29×10^4 m/m^3 within 0–5 mm of the fertiliser. Compared to untreated areas, values of L_v were significantly higher under the fertiliser to a depth of 400 mm. The combined sets of lateral and vertical samples suggested an asymptotic relationship between L_v and P_l (Fig. 6).

DISCUSSION

Soil Solution Phosphorus

The highly phosphorus-fixing nature of soil used in this study was indicated by the high degree of buffering inferred in Eq. [1]. The first derivative of Eq. [1] is the solid-liquid phase partition coefficient (K_d), which is the dominant component of buffer power if there is appreciable interaction with the solid phase (Van Rees *et al.* 1990). The K_d value is sometimes referred to as the buffer capacity (Sutter *et al.* 1996). At a P_l concentration of 0.4 μM, typical of untreated soil in this study, the K_d value was calculated to be 7600 *l*/kg, which indicates that P_l at these low concentrations was highly buffered (Smethurst *et al.* 1997). By comparison, a P_l concentration of 100 μM measured at the 18- and 42-month sites within 5 mm of the fertiliser confers a K_d value of 32 *l*/kg, which indicated moderate buffering of this concentration. Poorly buffered solutes have K_d values less than 10 *l*/kg (Smethurst *et al.* 1997).

A P_l concentration of 0.2 mg/*l* (6.5 μM) is considered adequate to support high growth rates of many plant species (Asher & Loneragan 1967; Fox 1981; Skinner & Attiwill 1981). The amount of phosphorus sorbed while raising the P_l to this value has been used as a basis for comparing phosphorus-fixing characteristics of soils. Relative to many other soils in the world, those derived from basalt in Hawaii (Fox *et al.* 1968) and ferruginous nodules from Ghana and Brazil (Tiessen *et al.* 1991) have very high phosphorus-fixing capacities. The

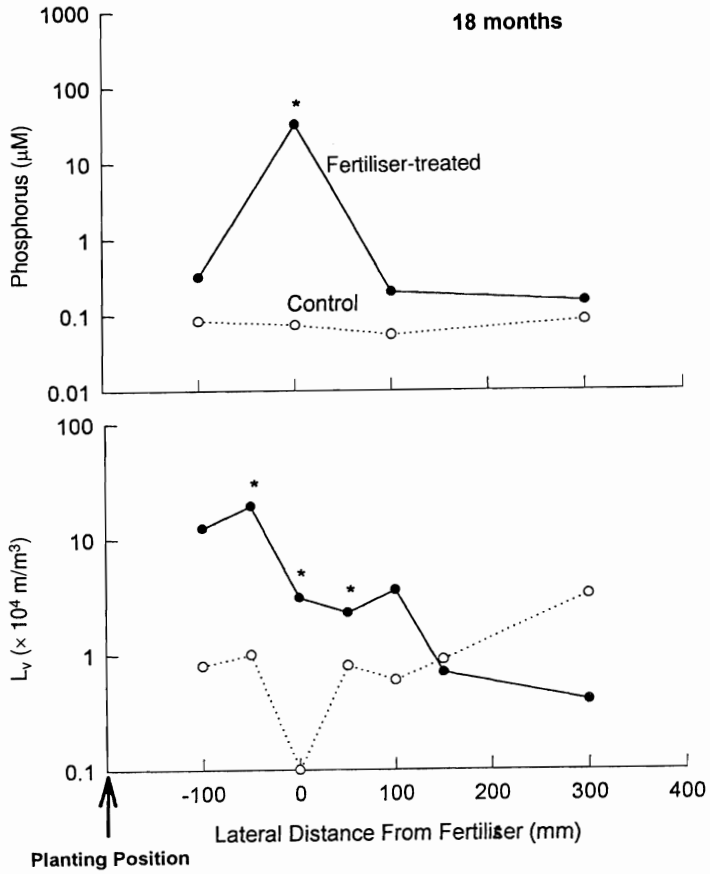

FIG. 4–Concentrations of phosphorus in soil solution (top) and root-length density (L_v; bottom) *v.* lateral distance for fertiliser-application (●) and control (○) sides of four trees in relation to the fertiliser-treated microsite or the equivalent position on the untreated side of the tree. Significant differences between control and fertiliser-treated values (as indicated by no overlap of the 95% confidence band) are indicated by an asterisk. Points are shown at the centre of the measurement zone.

amount of phosphorus sorbed at this concentration by our soil (also derived from basalt) was higher than that sorbed by ferruginous nodules, similar to soils derived from basalt in Hawaii, and lower than soils derived from volcanic ash (Table 1). There was a similar ranking of soils for the K_d value at this concentration, but the sorption maximum for our soil was higher than that for other basalt soils or ferruginous nodules. Because the amount of phosphorus sorbed increases with the duration of equilibration (Barrow 1983), and because our soils were equilibrated for only 17 h compared to 3 d used by Tiessen *et al.* (1991) and 6 d used by Fox *et al.* (1968), we infer that the soils used in the present study were amongst the highest phosphorus-fixing soils reported.

Slow lateral movement of phosphorus in amounts great enough to measurably increase P_l, i.e., to less than 100 mm after 18 months (Fig. 4), was confirmation that diffusion was slow in this soil due to the high degree of solid-liquid phase interaction, and that roots would

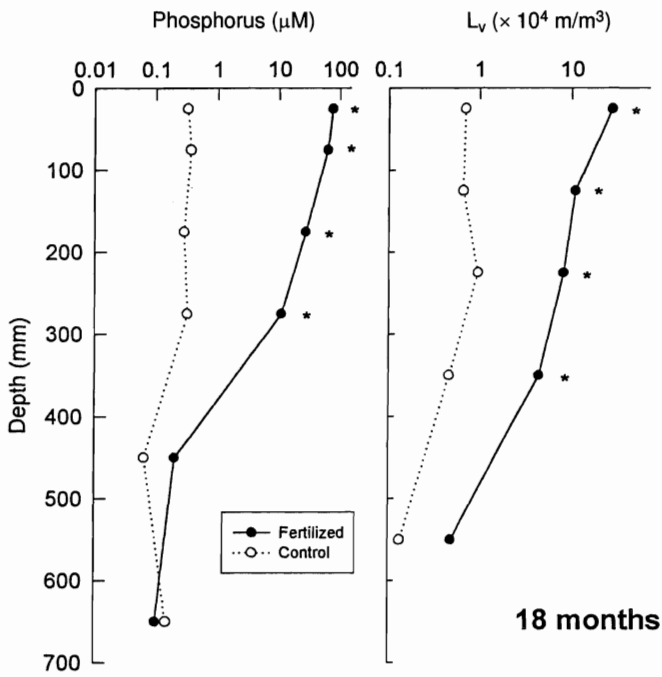

FIG. 5—Concentrations of phosphorus in solution (left) and root-length density (L_v; right) *v.* vertical distance for fertiliser-application (●) and control (○) sides of trees in relation to the fertiliser-treated spot or the equivalent position on the untreated side of the tree (n = 4). Differences in phosphorus concentrations were significant (*, $p < 0.05$) at 275 mm depth and shallower, and for L_v at 350 mm and shallower. Points are shown at the centre of the measurement zone.

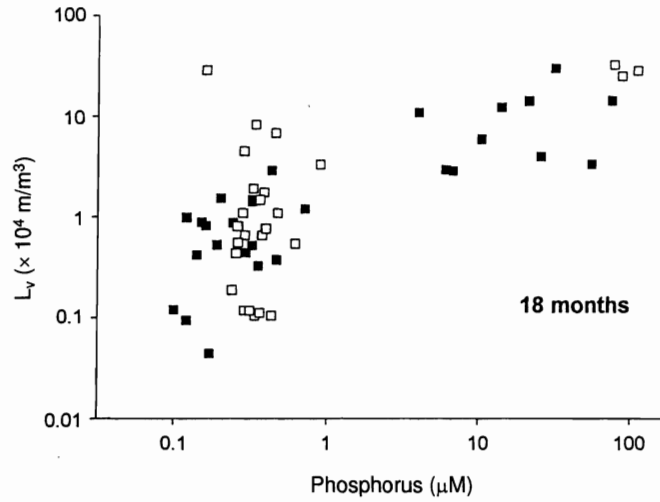

FIG. 6—Root-length density as a function of solution phosphorus for lateral (□) and vertical (■) samples taken 18 months after planting and fertiliser application.

TABLE 1–Phosphate sorption indexes of soil in the present study and some other highly phosphorus-fixing soils.

Source	Material	Phosphorus sorbed (mg/kg) *	K_d (*l*/kg) *	Sorption maximum (mg/kg)
Current study	Soil from basalt	472	217	5000†
Fox *et al.* (1968)	Soils from basalt	30–660	20–1000	NA–2538
Fox *et al.* (1968)	Soils from volcanic ash	540–1850	NA–8250	2715–NA
Tiessen *et al.* (1991)	Ferruginous nodules	147	NA	> 1000

* At 0.2 mg/*l* in solution
† Mendham (unpubl. data)
NA = not available

probably need to grow towards the fertiliser to benefit from it. Hence, the supply of phosphorus to newly planted seedlings in these soils might be enhanced by closer placement of the phosphorus fertiliser than was used in this study (20 cm), but there may be an increased risk of root damage if nitrogen is included in the fertiliser mix. The optimum volume of soil with which the phosphorus fertiliser reacts also needs examination; more than one spot per tree or band applications might be more beneficial, but broadcast applications are likely to be least effective.

The 2- to 42-month comparison of P_I concentrations (Fig. 3) should be treated cautiously because of inherent problems with the chronosequence approach, i.e., inferred differences might be due to site rather than changes occurring with time (e.g., Turvey & Smethurst 1989). Nevertheless, that concentrations of P_I around the fertiliser-treated microsites at all sites were much higher than those required for many plant species (Asher & Loneragan 1967; Fox 1981; Skinner & Attiwill 1981) suggests that adequate phosphorus availability was maintained for at least 42 months. Although this high phosphorus availability was concentrated in microsites, plants effectively access these localised sources of phosphorus (Jackson & Caldwell 1992), and microsite placement of fertiliser is commonly used to supplement the phosphorus supply to agricultural crops grown in highly phosphorus-fixing soils (Moody 1994).

Leaching apparently contributed to the downward movement of phosphorus because the rate of spread downwards was greater than that laterally (Fig. 4 and 5). Because the soil was moderately well structured and cultivation introduced clearly evident macropores, it is likely that there was incomplete equilibration of phosphorus between the solid and liquid phases as water percolated through the profile, i.e., by-pass flow. Other authors have similarly speculated about the role of macropores in the downward movement of phosphorus from fertiliser-treated microsites (Nayakekorola & Woodard 1995; White 1996). Downward movement of solute can be increased also by the high specific-gravity of solution in treated microsites in the phenomenon of fertiliser "drop-out" (Bonczek & McNeal 1996; Glass *et al.* 1989). Although we could not assess the relative importance of these mechanisms in our study, results indicate that leaching of phosphorus did occur under fertiliser-treated microsites despite very high phosphorus-fixing conditions.

Roots

Root growth of many species is enhanced in nitrogen- or phosphorus-fertile microsites (Nye & Tinker 1977; Eissenstat & Van Rees 1994; Barber 1995), but it had not been recorded

previously for *E. nitens* (Fig. 4–6). Values of L_v in surface soil without fertiliser were approximately $1 ¥ 10^4$ m/m^3 18 months after planting (Fig. 5), i.e., about double the values observed for *P. radiata* plantations of a similar age (Nambiar 1990), which is probably attributable partly to the small diameter of most *E. nitens* fine roots. For example, the modal diameter of *E. nitens* fine roots is 0.2–0.3 mm (Misra pers. comm.) compared to 0.4 mm for *P. radiata* (Nambiar 1981). Barrow (1977) also found that the modal diameter of roots of three eucalypt species was 0.1–0.2 mm compared to 0.5 mm for *P. radiata*. Values of L_v for *E. nitens* increased to about $30 ¥ 10^4$ m/m^3 in the fertile microsites, a value similar to pasture grasses and wheat crops under some conditions (Nambiar 1990). These data suggest that root proliferation is an important mechanism used by this species to maximise the uptake of a limiting nutrient from fertile microsites, and that maximum L_v is reached between 1 and 10 μM P.

The relationship between P_I and L_v (Fig. 6) is confounded by the possibility that root growth was affected by increased nitrogen availability after fertiliser application. Because this relationship may be specific to the conditions of the study it should be used cautiously when applying it to eucalypt root growth elsewhere. The response of *E. nitens* roots to NP-fertiliser should be considered further in developing our understanding of nitrogen and phosphorus acquisition in these plantations.

CONCLUSIONS

Several conclusions can be drawn from this study. Spatial and temporal patterns in P_I were evident after application of phosphorus fertiliser, including evidence that fertiliser phosphorus leached at least 300 mm below the point of application despite the high phosphorus-fixing characteristics of this soil. Concentrations of P_I close to the point of application remained high for at least 42 months after treatment. Since eucalypt roots proliferated in these fertile zones, microsite applications of fertiliser were an effective way of maintaining high phosphorus availability to *E. nitens* during at least the first 42 months of the crop.

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