TREE STOCKING EFFECTS ON SOIL CHEMICAL AND MICROBIAL PROPERTIES AT THE TIKITERE AGROFORESTRY RESEARCH AREA

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ABSTRACT

Soil fertility at the Tikitere Agroforestry Research Area near Rotorua has been monitored since the site was planted with *Pinus radiata* D. Don in 1973. Measurements made in 1991 and 1992 showed that after 18 years soil pH had declined and that Olsen phosphorus levels increased with increased tree stocking. Soil magnesium also declined at the higher tree stocking rates. We made further measurements on samples collected in 1991 and 1992 to determine reasons for the change in nutrient status.

Soil carbon and soil organic phosphorus in the surface soil (0–75 mm depth) decreased with tree stocking, indicating increased net mineralisation of soil organic matter under *P. radiata* compared with pasture. Exchangeable cations and cation exchange capacity also declined with tree stocking, which is consistent with the loss of exchange sites in soil organic matter. Total soil inorganic phosphorus declined with increased tree stocking. This was expected because of reduced fertiliser phosphorus input at the higher stocking rates. However, phosphorus fractionation showed that bicarbonate-extractable inorganic phosphorus increased and acid-extractable inorganic phosphorus declined with tree stocking. The latter indicated possible decreases in soil apatite phosphorus.

These results were consistent with the mobilisation of soil phosphorus under *P. radiata* by dissolution of fluorapatite (in parent material deposited during the 1886 Tarawera eruption) due to lower soil pH values and mineralisation of organic phosphorus previously accumulated under pasture. Consequently, Olsen phosphorus has increased despite reduced phosphorus fertiliser applications. Microbiological activity (as indicated by microbial biomass and microbial respiration) and phosphatase activities of soil samples collected in 1995 also decreased with tree stocking, and so mineralisation of organic matter was not a result of microbial activity alone. However, the proportion of soil aggregates > 0.5 mm decreased under *P. radiata*, indicating there was less physical protection of the soil organic matter than under pasture where soil aggregates were maintained by fine roots.

Keywords: aggregates; agroforestry; fluorapatite; microbial biomass; Olsen phosphorus; physical protection; phosphorus fractions; phosphatase activity; soil chemistry; soil organic matter; *Pinus radiata.*

INTRODUCTION

Because of demand for land for forestry, and the reduced profitability of sheep and beef farming in New Zealand, *Pinus radiata* is being grown on some pastoral farms. Consequently, there is an interest in the effect of *P. radiata* on soil properties and soil fertility in agroforestry systems incorporating both pasture and pine. Any changes in soil properties under pine could also influence choices for post-harvest land use.

Effects of *P. radiata* on soil properties at a range of tree stockings were investigated at the Tikitere Agroforestry Research Area near Rotorua, North Island, New Zealand. The trial was on a Rotoiti sandy loam, a recent volcanic loam (typic Vitrudand), and the site had a temperate climate and mean annual rainfall of 1600 mm, generally evenly distributed. After a 50- to 60-year history of pastoral use (sheep, cattle, and dairy) the site was planted in *P. radiata* in 1973. Plantings were made at 0, 250, 500, 1000, and 2000 stems/ha. Each stocking treatment covered 8 ha in four 2-ha replicated blocks, surrounded by a 28-m buffer zone. The initial stocking rates were reduced over an 8-year period to final-stocking rates of 0, 50, 100, 200, and 400 stems/ha.

Pasture production decreased in relation to increases in tree stocking and tree age, and the contribution of white clover and ryegrass declined over time under the trees (Hawke 1991). Wood volume and basal area growth increased with tree age and tree stocking.

The site was aerially topdressed from 1975 to 1983 with 15% or 30% potassic superphosphate at 200–250 kg/ha. From 1983 there were variations in the fertiliser application, depending on the tree stocking regimes (Hawke & O'Connor 1993). Total fertiliser phosphorus applied is listed in Table 1. During the trial period sheep were rotationally grazed at the site, with animal stocking rates dependent on the available pasture.

TABLE 1–Total fertiliser phosphorus applied 1975–92 (mean of blocks)*

Tree stocking (stems/ha)	Fertiliser phosphorus (kg P/ha)
0	305
50	278
100	219
200	151
400	120

* Calculated according to Hawke & O'Connor (1993).

Yeates (1988) found a decline in earthworm numbers at this site after 13 years and concluded that changes in soil biological activity could influence post-harvest land management. After 20 years, soil pH had decreased and Olsen phosphorus increased with tree stocking (Hawke & O'Connor 1993). Other workers (Belton *et al.* 1995; Condron *et al.* 1996; Davis 1995; Davis & Lang 1991) have also found increases in extractable soil phosphorus under pine and attributed this to enhanced mineralisation of organic soil phosphorus.

To investigate reasons for the change in nutrient status at the Tikitere site, we determined the forms of phosphorus in soil samples collected in 1991 and 1992. We also measured some soil microbiological and biochemical characteristics of fresh soil samples collected in 1995. The results of this work are reported here.

MATERIALS AND METHODS

Soil samples were taken at random within plots (i.e., with no relationship to trees) using a standard 25-mm-diameter corer. Usually about 80–100 cores were collected below the decomposing needle layer and a subsample of 15–20 cores (0–75 mm depth) was taken for analysis. Details of previous soil chemical measurements have been reported by Hawke & O'Connor (1993).

Soil samples taken in 1991 (0–75 mm) and 1992 (0–30 mm, 30–75 mm, 75–150 mm, and 150–300 mm) were air dried (35°C), crushed, and sieved to <2 mm. These samples were analysed for cation exchange capacity (Searle 1986), exchangeable cations (Searle 1986), and phosphate retention (Saunders 1965). Sub-samples were ground in a ring grinder and then in a mortar and pestle until all the soil passed through a 150-μm sieve. These were analysed for organic carbon (Dalal 1979a, b), total phosphorus, and organic phosphorus by an ignition method (Blakemore *et al.* 1972; Saunders & Williams 1955). The ignition method also provided values of total inorganic phosphorus (Pi) extractable in sulphuric acid. A sequential extraction procedure similar to that of Perrott *et al.* (1989) (1 M NaCl followed by 0.5 M $NaHCO_3$ pH 8.5, 1 M NaOH, 0.5 M H_2SO_4, and a final determination of residual organic phosphorus remaining in the sample) was used to determine both inorganic phosphorus and organic phosphorus fractions. Inorganic phosphorus was determined by the method of Murphy & Riley (1962). Total phosphorus in the sodium bicarbonate and caustic soda extracts was determined as inorganic phosphorus after digestion with nitric acid/perchloric acid, and organic phosphorus was calculated by subtracting inorganic phosphorus. No organic phosphorus was found in the sulphuric acid extracts. The inorganic phosphorus extracted from the sample by 0.5 M H_2SO_4 after previous extraction with sodium bicarbonate, caustic soda, and sulphuric acid, and ignition of the sample at 550°C, was assumed to be residual organic phosphorus.

Similar soil samples taken in 1995 (0–75 mm) were sieved (5.6 mm followed by 4 mm) whilst field-moist, vegetative material was removed and the samples were mixed thoroughly and stored moist at 4°C until used. These field-moist soil samples were analysed for phosphomonoesterase and phosphodiesterase (Browman & Tabatabai 1978; Tabatabai & Bremner 1969 as modified by Sarathchandra & Perrott 1981). The other measurements made on these samples were microbial carbon (Vance *et al.* 1987 as modified by Wardle & Ghani 1995), substrate-induced respiration (Wardle & Ghani 1995; West & Sparling 1986), basal respiration (Wardle & Ghani 1995), and microbial phosphorus (Brookes *et al.* 1982; Perrott & Sarathchandra 1989). After air drying at 35°C, these samples were analysed for hot-water-extractable carbohydrate by extracting 3 g soil with 30 ml water at 20°C for 30 min by end-over-end shaking (20 rpm), discarding the supernatant after centrifugation, adding another 30 ml water, mixing thoroughly, and heating in a water bath at 80°C for 16 h. Carbohydrates in the supernatant solution were determined by the method of Safařík & Santrůčková (1992), after centrifugation and microfiltration (0.45 μm). The aggregate size distributions of the air-dried soils were determined by wet sieving through nested sieves after end-over-end shaking

(20 rpm) in water (20 g soil and 100 ml water in 150-ml flask) for 10 min. The sand and pumice contents of the aggregates and whole soil were determined by sonicating them in approximately 50 ml of water (100W, 20KHz for 5 min) and sieving through a 38-µm sieve.

Statistical analysis of the data was performed using the ANOVA directive of the statistical package Genstat where the ordered structure of treatments was taken into account. The treatments were blocked on aspect and this was accounted for in the ANOVA.

RESULTS

Soil Chemistry

Significant effects of increased tree stocking were found for cation exchange capacity ($p < 0.01$), exchangeable cations ($p < 0.001$ for calcium and sodium, $p < 0.01$ for magnesium and $p < 0.05$ for potassium), organic carbon ($p < 0.01$), and soil phosphorus ($p < 0.01$ for total and inorganic phosphorus and $p < 0.001$ for organic phosphorus) (Fig. 1a, b; Fig. 2a, b). No effects were apparent for phosphorus retention (Fig. 2a). Most soil chemical characteristics decreased with increased tree stocking, the greatest change occurring between 0 and 200 stems/ha.

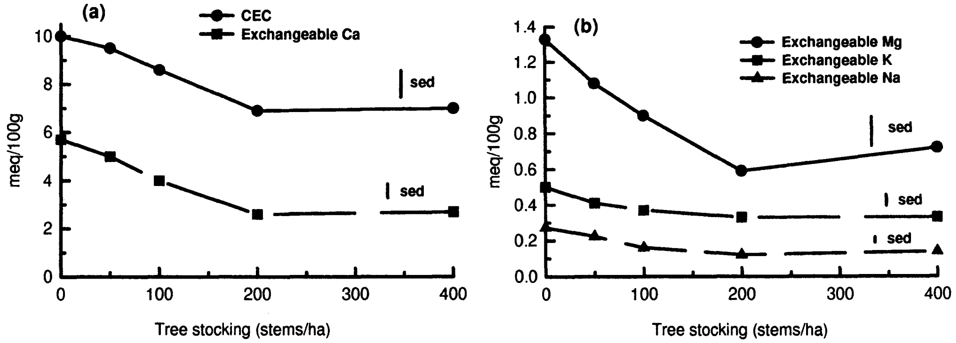

FIG. 1–Influence of tree stocking on (a) soil cation exchange capacity and exchangeable calcium; (b) soil exchangeable magnesium, potassium, and sodium for 0–75 mm depth in 1991. Values expressed on weight basis, s.e.d. = standard error of difference.

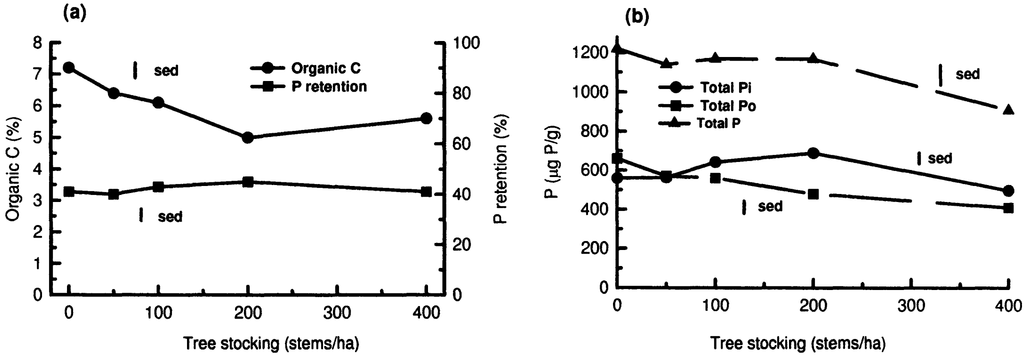

FIG. 2–Influence of tree stocking on (a) soil organic carbon and phosphorus retention; (b) total soil phosphorus, total soil inorganic phosphorus, and total soil organic phosphorus for 0–75 mm depth in 1991. Values expressed on weight basis, s.e.d. = standard error of difference.

Total phosphorus determined by ignition was approximately 90% of the total phosphorus content of selected samples determined by a sodium carbonate fusion method (Blakemore *et al.* 1972). The values of total phosphorus and total inorganic phosphorus determined by the simpler ignition method were therefore used as convenient measures of the absolute total phosphorus and inorganic phosphorus. Whereas both total phosphorus and total organic phosphorus decreased with increased tree stocking, the total inorganic phosphorus increased up to 200 stems/ha, but was lower at 400 stems/ha (Fig. 2b).

Soil Phosphorus Fractions

The soil phosphorus fractions for the 0–75 mm samples from 1991 are indicated in Fig. 3a and 3b. While the changes with tree stocking for the sodium bicarbonate-inorganic phosphorus fraction were not statistically significant, changes were significant for the caustic soda-inorganic phosphorus and sulphuric acid-inorganic phosphorus fractions ($p < 0.01$ for both). The caustic soda-inorganic phosphorus (which was the largest inorganic phosphorus fraction) increased with tree stocking up to 100 or 200 stems/ha, and then decreased between 200 and 400 stems/ha. There was an overall decline in the acid inorganic phosphorus fraction with increasing tree stocking. The largest organic phosphorus fraction (caustic soda-organic phosphorus) declined significantly ($p < 0.05$) with increased tree stocking, as did the residual-organic phosphorus (the organic phosphorus fraction remaining after completion of the sequential extractions) ($p < 0.001$). However, there did not seem to be a consistent significant trend in sodium bicarbonate-organic phosphorus values with tree stocking.

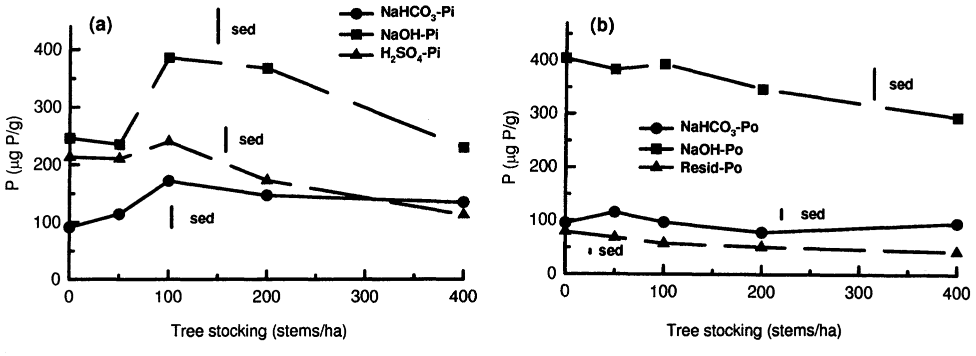

FIG. 3–Influence of tree stocking on soil phosphorus fractions (a) sodium bicarbonate-inorganic phosphorus, caustic soda-inorganic phosphorus, and sulphuric acid-inorganic phosphorus; (b) sodium bicarbonate-organic phosphorus, caustic soda-organic phosphorus, and residual organic phosphorus. Values expressed on weight basis, .se.d. = standard error of difference.

Influence of Depth on Tree Stocking Effects

Analysis of the soil samples taken in 1992 provided information on the tree stocking effects at four depths. Tree stocking effects generally declined with depth (Fig. 4a, b, c). In these diagrams the differences between the 200 stems/ha and 0 stems/ha treatments are expressed on a weight basis for the different depths. Significant changes occurred only in the top two depths (0–30 mm and 30–75 mm). The same situation occurred with the soil phosphorus fractions where differences between the 400 stems/ha and 0 stems/ha treatments

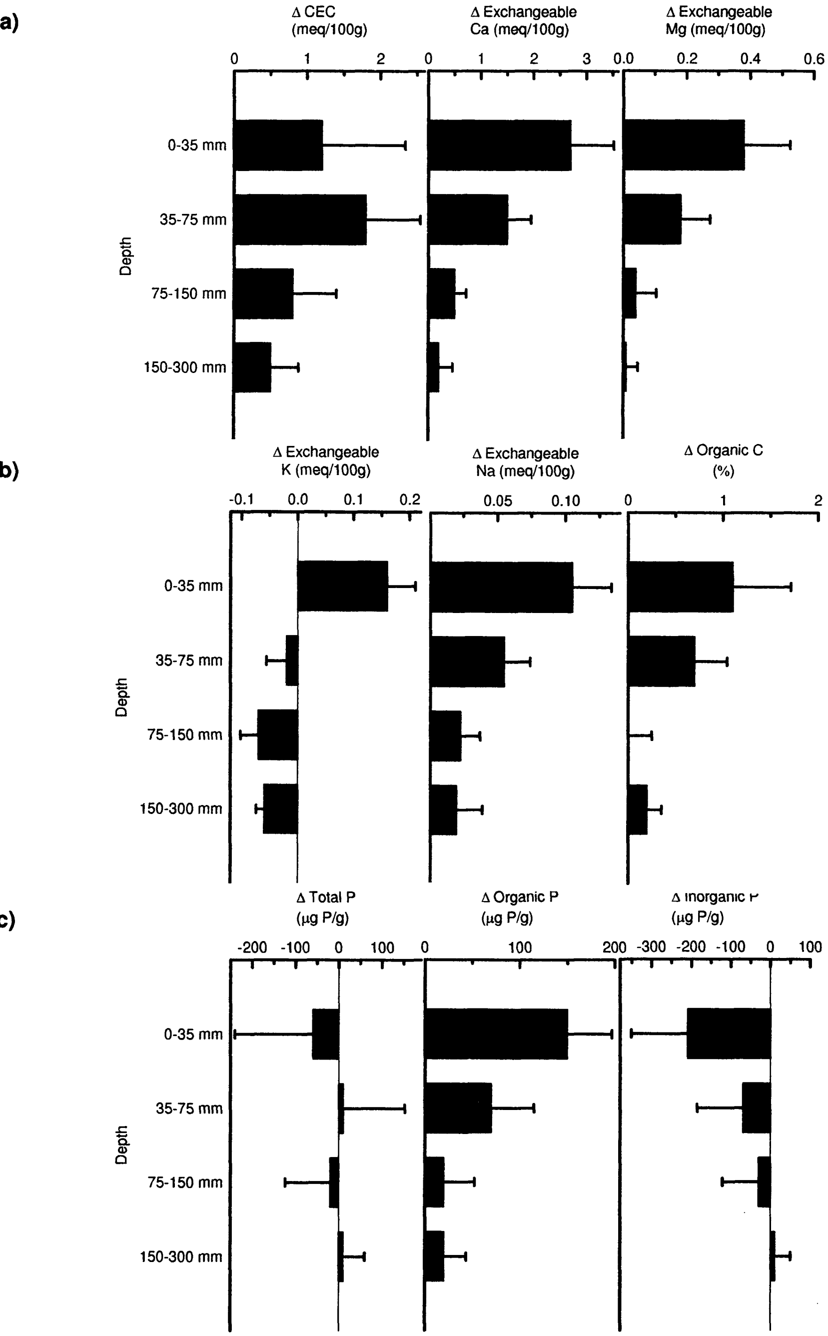

FIG. 4—Influence of soil sample depth on tree stocking effects for (a) cation exchange capacity, exchangeable calcium, and exchangeable magnesium; (b) exchangeable potassium, exchangeable sodium, and organic carbon; (c) total soil phosphorus, total organic phosphorus, and total inorganic phosphorus. (Values at 200 stems/ha subtracted from values at 0 stems/ha.) Values expressed on weight basis. Error bar = standard error of mean.

were used for caustic soda-organic phosphorus and sulphuric acid-inorganic phosphorus, and differences between 100 stems/ha and 0 stems/ha treatments were used for the caustic soda-inorganic phosphorus fractions (Fig. 5).

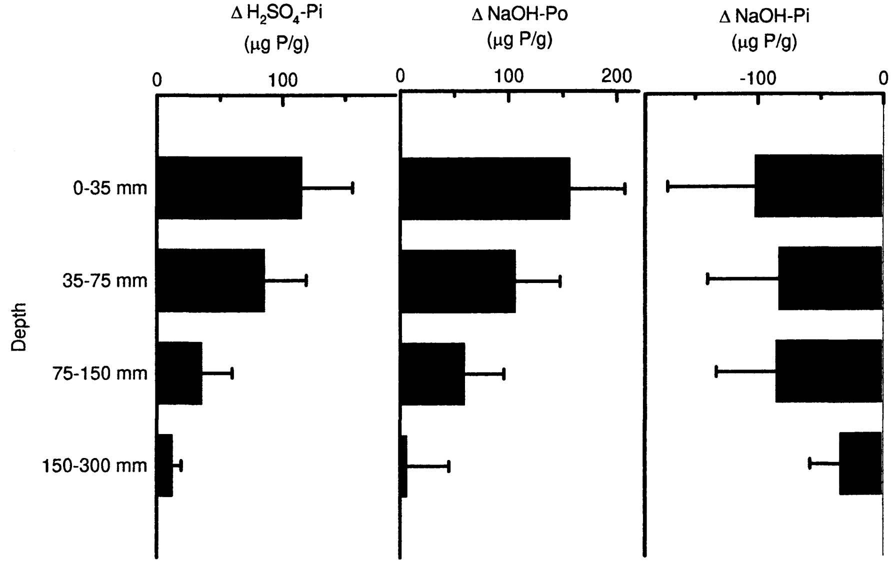

FIG. 5–Influence of soil sample depth on tree stocking effects for major phosphorus fractions. (Values at either 400 stems/ha {ΔH_2SO_4-Pi and ΔNaOH-Po} or 100 stems/ha {ΔNaOH-Pi} subtracted from values at 0 stems/ha). Values expressed on weight basis. Error bar = standard error of mean.

Microbial and Enzyme Activities

The effect of tree stocking on phosphohydrolase activity, basal respiration, substrate-induced respiration, and the microbial carbon and phosphorus values was similar to that observed with most soil chemical characteristics. There was a decline of values with increased tree stocking ($p < 0.001$ for the phosphatases and substrate-induced respiration, $p < 0.01$ for microbial phosphorus and carbon, and $p < 0.05$ for basal respiration), the largest change generally occurring between 0 and 200 stems/ha (Fig. 6a, 6b, 7). No measurements were made of microbial activity at other soil depths.

Aggregate Size Distribution and Water-extractable Carbohydrates

The aggregate size ranges for the soil samples collected in 1995 showed two different patterns for changes with tree stocking—aggregates > 0.5 mm had a common pattern which was different to that for aggregates < 0.5 mm. The aggregate size distributions were therefore expressed as proportion > 0.5 mm and proportion < 0.5 mm (Fig. 8). The data were corrected for sand and pumice content of the soil and aggregates and expressed on a sand-free basis. Under pasture about 60% of the aggregates were > 0.5 mm. This proportion declined with tree stocking ($p < 0.01$). A similar pattern occurred with the hot-water-extractable carbohydrate ($p < 0.001$) (Fig. 8).

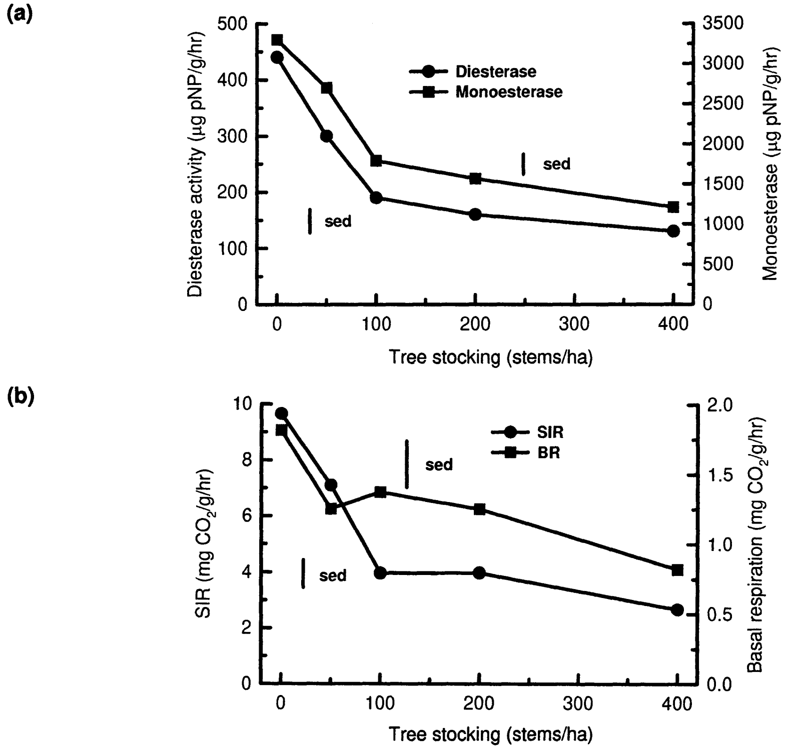

FIG. 6–Influence of tree stocking on (a) phosphomonoesterase and phosphodiesterase activities; (b) basal respiration and substrate-induced respiration for 0–75 mm depth in 1995. Values expressed on weight basis, s.e.d. = standard error of difference.

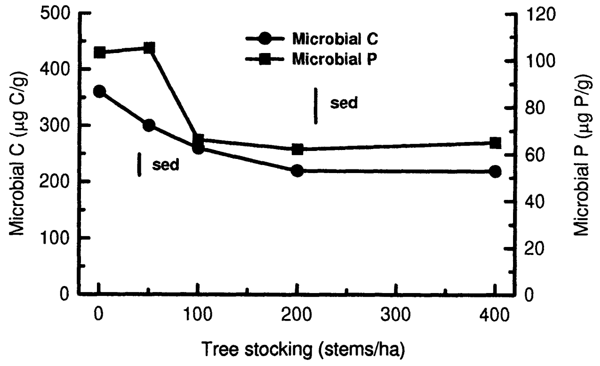

FIG. 7–Influence of tree stocking on soil microbial carbon and phosphorus for 0–75 mm depth in 1995. Values expressed on weight basis, s.e.d. = standard error of difference.

Changes on a Volume and Area Basis

Hawke & O'Connor (1993) found that the soil bulk density at this site decreased with tree stocking. When this was taken into account and the soil chemical changes were calculated on an area basis, the effects of tree stocking appeared more marked (Fig 9).

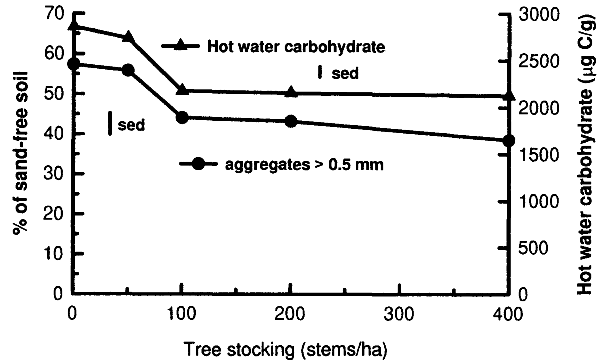

FIG. 8–Influence of tree stocking on soil aggregate size distribution and hot-water-extractable carbohydrate. Values expressed on weight basis, s.e.d. = standard error of difference.

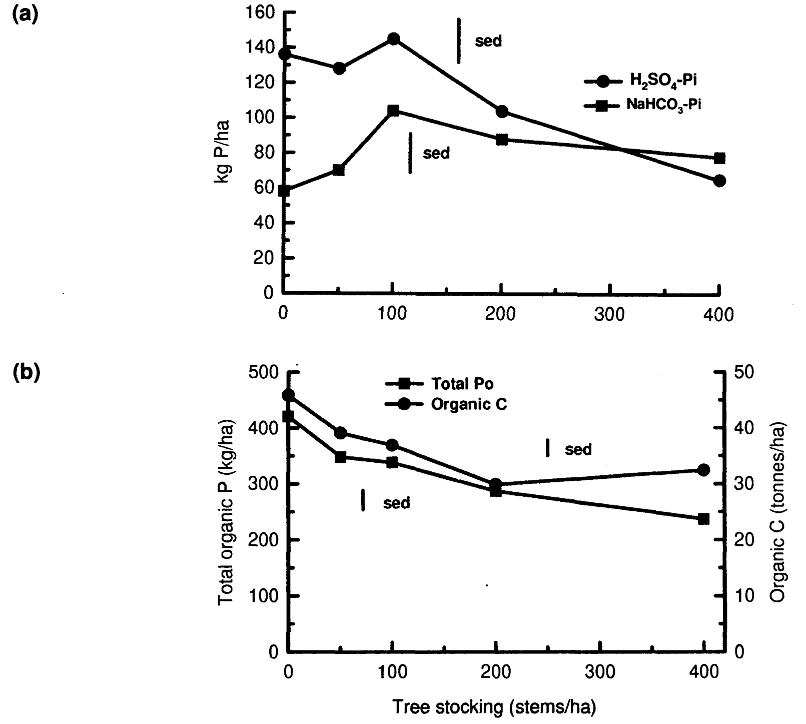

FIG. 9–Influence of tree stocking on some measured soil properties expressed on a weight per area basis for 0–75 mm depth in 1991: (a) soil phosphorus fractions sulphuric acid-inorganic phosphorus and sodium bicarbonate-inorganic phosphorus; (b) total organic phosphorus and organic carbon. S.e.d. = standard error of difference.

DISCUSSION

Hawke & O'Connor (1993) reported increases in Olsen phosphorus and sulphate sulphur, and decreases in soil pH, with increased tree stocking at this site. "Quick Test" magnesium and "Quick Test" calcium also decreased with tree stocking, and this is consistent with our finding of decreases in cation exchange capacity and exchangeable cations with tree stocking. These properties showed a similar pattern to that of organic carbon, in that most of the decline occurred between 0 and 200 stems/ha. This suggests that changes in the amount of exchangeable cations held by the soil resulted from the reduction of exchange sites present in soil organic matter as well as removal by tree uptake. The reduction in cation exchange capacity and exchangeable cations could also have resulted from the reduction of variable charge and base saturation of the soil organic matter with the decrease in soil pH (Zelazny *et al.* 1996).

The decline of total phosphorus with increased tree stocking was not surprising considering the associated reduced inputs of fertiliser phosphorus (Table 1). However, the decline in organic phosphorus (and soil organic matter) indicated that *P. radiata* either reduced the build-up of organic phosphorus (and organic matter) compared with pasture, or caused an increase in net mineralisation of organic phosphorus (and organic matter). Other workers have also noted a decrease in organic phosphorus under pine, indicating net mineralisation of organic phosphorus (Belton *et al.* 1995; Condron *et al.* 1996; Davis 1995; Davis & Lang 1991).

The decline in inorganic phosphorus under higher stocking rates of pine was not consistent with the reported increase in Olsen phosphorus (Condron *et al.* 1996; Davis 1995; Hawke & O'Connor 1993). However, phosphorus fractionation indicated that bicarbonate extractable inorganic phosphorus varied in a similar way to Olsen phosphorus (increasing to 100 stems/ha and remaining approximately constant at higher tree stocking rates). Similarly, caustic soda-inorganic phosphorus (which is the largest inorganic phosphorus fraction and is present in aluminium-inorganic phosphorus and iron-inorganic phosphorus forms) increased at stockings up to 100 stems/ha but then declined to 400 stems/ha, as did the total inorganic phosphorus. The increase in Olsen phosphorus under pine in the absence of fertiliser phosphorus inputs has been attributed to the release of phosphorus when organic matter is mineralised (Condron *et al.* 1996; Davis 1995). However, the fractionation results indicate a decrease in sulphuric acid-inorganic phosphorus as well as the major organic phosphorus fractions under pine. Therefore, the sulphuric acid-inorganic phosphorus fraction may have also contributed to the increase in Olsen phosphorus values.

Although both total organic phosphorus and sulphuric acid-inorganic phosphorus decreased with tree stocking increases from 0 to 400 stems/ha, Olsen phosphorus did not increase significantly from stocking rates of 100 to 400 stems/ha. Reduced fertiliser phosphorus input at the higher tree stocking rates (Table 1) explains this. The pattern of Olsen phosphorus changes with tree stocking rate will have resulted from fertiliser phosphorus inputs, mineralisation of organic phosphorus, release of phosphorus from sulphuric acid-inorganic phosphorus, phosphorus uptake by trees, and phosphorus export by animals during the 20 years of the trial.

The sulphuric acid-inorganic phosphorus fraction includes apatite phosphorus. Although some of this could have originated from unacidulated phosphate rock in the superphosphate fertiliser used, the amounts of sulphuric acid-inorganic phosphorus present (approximately 140 kg P/ha at 0 stems/ha) are very large compared with the amount of superphosphate phosphorus applied (about 300 kg P/ha at 0 stems/ha). Superphosphate manufactured during the 1973–91 period contained less than 5% unacidulated phosphate rock (M.W.Brown pers.

comm.) and the sulphuric acid-inorganic phosphorus fraction would largely represent native soil fluorapatite. The decline in sulphuric acid-inorganic phosphorus under pine is consistent with dissolution of native soil fluorapatite. The sulphuric acid-inorganic phosphorus also decreased with depth, indicating higher amounts of fluorapatite in surface layers (Table 2).

TABLE 2–Changes in sulphuric acid-inorganic phosphorus with depth in 1992 soil samples at 0 stems/ha.

Soil layer (mm)	Sulphuric acid-inorganic phosphorus (μg P/g)
0–35	234
35–75	180
75–150	121
150–300	49
Mean s.e.*	26.6

* Standard error of difference

The soil, Rotoiti sandy loam, had a 25–75 mm surface layer of rhyolitic Rotomahana mud (derived from the Tarawera eruption in 1886) on Kaharoa ash and Taupo ash (New Zealand Soil Bureau 1954). The surface layers therefore contained recently added, and hence relatively unweathered, material. Although rhyolitic material does not contain high amounts of P (Saunders (1968) gave a figure of about 600 μg P/g), this layer probably contributed significantly to the total soil phosphorus because of its relatively unweathered state. The phosphorus present in the unweathered material would be present as fluorapatite (McKelvey 1973; Nash 1984) and in fact Fieldes & Weatherhead (1968) detected apatite in the Rotomahana recent soil which is formed on Rotomahana mud. We also detected apatite in the heavy sand fractions of the Rotoiti surface soil extracted by heavy liquid sedimentation. Kocher'Yan (1989) suggested a similar addition of acid soluble apatite in volcanic ash additions to surface soils to explain high extractable-phosphorus levels with acidic extractants.

The lower pH under *P. radiata* (Hawke & O'Connor 1993) probably caused the fluorapatite dissolution. Calcium-chelating organic acids, such as citric and oxalic, are produced by roots and by soil and litter fungi under pine (Cumming & Weinstein 1990; Fox & Comerford 1990, 1992a; Malajcczuk & Cromack 1982), and these may accelerate fluorapatite dissolution (Cromack *et al.* 1979; Graustein *et al.* 1977; Jurinak *et al.* 1986; Malajcczuk & Cromack 1982). The data for the surface layers of the Tikitere site indicate that the percentage saturation of the exchange complex with calcium reduced with increased tree stocking (Table 3) and this is also consistent with the removal of calcium by chelating organic acids.

An alternative explanation for the decline of sulphuric acid-inorganic phosphorus with tree stocking could be the release of soil phosphorus occluded by iron oxides (or the inhibition of phosphorus occlusion by iron oxides) under *P. radiata*. Organic acids produced by the soil and litter fungi and by roots could be responsible. However, this mechanism would also be expected to reduce the phosphate retention capacity of the soil by removal, or inactivation, of hydrous iron and aluminium oxides. The lack of a significant change in phosphorus retention indicates that this was unlikely, although the specific measurements made may not have been sensitive enough to detect such a change.

TABLE 3–Effect of tree stocking on percentage saturation of exchange complex with calcium (1992 samples, 0–75 mm)

Tree stocking (stems/ha)	Calcium saturation of exchange sites (%)
0	58
50	52
100	50
200	38
400	37
s.e.*	7.7

* Standard error of difference

Increased mineralisation of organic phosphorus has been attributed to release of phosphohydrolases by pine roots and associated ectomycorrhizal fungi (Berthelin *et al.* 1991; Condron *et al.* 1996; Fox & Comerford 1992b; Kieliszewska 1990; MacFall *et al.* 1991; Pasqualini *et al.* 1992). However, in this study phosphoesterase activities were actually highest under pasture and decreased with tree stocking. A similar situation occurred with the measures of microbial activity. Earlier measurements, made when the trees were 13 and 15 years old, also showed that both microbial biomass carbon and mineralisable nitrogen decreased with increased tree stocking (Sparling *et al.* 1989). It appears that the pasture ecosystem has a greater level of soil organic matter, microbial activity, and enzyme activity than the pine ecosystem.

Greater microbial and enzyme activity does not necessarily imply greater net mineralisation of organic matter and organic phosphorus because the activity could be associated more with immobilisation of carbon and phosphorus. However, the fact that the measured phosphoesterase activities decreased under pine indicates that the observed organic phosphorus decline was not caused by enzyme activity alone.

It is possible that *P. radiata* reduced the effect of mechanisms protecting soil organic matter from mineralisation under pasture. Organic acids produced under pine could compete for adsorption sites on soil inorganic colloids (Cajuste *et al.* 1996). They could also solubilise metal phytates (Lapeyrie *et al.* 1991) and similar compounds. This would enable greater exposure of soil organic matter and organic phosphorus to microbiological and biochemical decomposition processes under pine than under pasture, despite the lower microbial activity.

Another protection mechanism operating under pasture is the physical protection of organic matter in soil aggregates (Beare *et al.* 1994; Cambardella & Elliott 1993; Eriksen *et al.* 1995a, b; Jastrow *et al.* 1996) whose formation and stability are encouraged by the high organic matter levels and prevalence of fine grass roots. With disappearance of these roots under pine, the stability of these aggregates would decrease and previously protected soil organic matter and organic phosphorus would then be exposed to microbial mineralisation processes. This was confirmed by the data for aggregate size distribution which showed that the proportion of aggregates > 0.5 mm declined with tree stocking. Similarly, both hot- and cold-water-extractable carbohydrates, which have been associated with aggregate stability (Haynes & Swift 1990), declined with tree stocking. The change in aggregate size distribution indicates the occurrence of a "deprotection" mechanism (Balesdent *et al.* 1998; Van Veen & Paul 1981) enabling greater decomposition of organic matter and organic phosphorus under *P. radiata* than under pasture.

CONCLUSION

Increases in Olsen phosphorus with increased tree stocking at the Tikitere Agroforestry Research Area can be explained by mineralisation of organic phosphorus previously built up under pasture and by dissolution of soil fluorapatite. Much of the soil fluorapatite may have derived from the Tarawera eruption of 1886. Mineralisation of organic phosphorus cannot be explained by changes in soil microbial activity, which was found to reduce with increased tree stocking. However, competition for adsorption sites by anions of organic acids, the desorption or dissolution of organic species, and the breakdown of soil aggregates could have exposed previously protected soil organic matter, thus enabling the mineralisation of organic phosphorus. Mineralisation of soil organic matter and lowering of soil pH by organic acids also explains the reduction in cation exchange capacity and exchangeable cation levels.

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