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PHOSPHORUS LEVELS IN TOPSOILS UNDER CONIFER PLANTATIONS IN CANTERBURY HIGH COUNTRY GRASSLANDS

M C Belton, K F O'Connor, A B Robson

Abstract

Topsoils under planted conifer forests in the Canterbury high country have high levels of 0.5 *M* H_2SO_4-P (inorganic P) compared to published records from topsoils of grasslands on soils of the same high country soil groups. Group means under conifers were from 16 per cent to 140 per cent higher than under grassland but such differences did not appear to be consistently related to moisture class or natural fertility. Concentrations of 0.5 h Olsen-P in conifer topsoils were also compared with topsoil records for unimproved grassland, semi improved grassland, and improved pasture for the same soil sets and soil groups. For forest topsoil samples, inorganic P and Olsen-P values were correlated, especially within the naturally more fertile groups of drier and younger soils. Both forests and grasslands exhibited a similar but small decline in Olsen-P values with increasing precipitation. For most soil taxa, variability in Olsen-P was high under any vegetation cover, but Olsen-P was clearly greater under conifer plantation than under grassland. Soils from the three development classes of grassland had similar mean Olsen-P levels whereas the average forest Olsen-P levels were generally 2 to 4 times higher than the average grassland level for the corresponding soil.

The data presented indicate a significant enhancement of "plant available" topsoil phosphorus by conifer plantations in the montane zone across a wide precipitation range. Despite the high variability, this enhancement appears to be of similar magnitude along the whole precipitation range sampled, a situation apparently different from that outlined for "inorganic P". This general situation is discussed in terms of possible processes suggested from earlier research.

INTRODUCTION

The impact of coniferous plantations on soil properties has been a topic of interest or concern among land use scientists for most of this century. It has been identified as an area of concern in a recent review of environmental effects of tree plantations in New Zealand (Rosoman,1994). Internationally the topic has been in part reviewed by Hornung (1985) in an assessment of acidification of soils by trees and forests. A critical examination of the evidence for particular tree species effects on soils has been compiled by Binkley (1994). Reviews of the effects of plantation forestry on New Zealand soils by Will & Ballard (1976) and Will (1993) have indicated that in some instances beneficial influences may occur. The phenomenon of increased availability of nitrogen (N) and phosphorous (P) in the root zone of conifers was examined by Fisher & Stone (1969) where pines had been planted for 10 to 14 years into the secondary succession vegetation of fields abandoned from agriculture in New York State. They found evidence consistent with greater N and P mineralisation or other extraction from organic matter apparently residual from the successional vegetation. Later, Fisher (1989) reviewed evidence for five possible mechanisms by which trees might ameliorate soils "degraded by exploitative agricultural practices". In New Zealand, Davis & Lang (1991) examined nutrient availability and other chemical soil properties in topsoils at comparative sites of exotic conifers and adjacent undeveloped grasslands at eight locations in inland Canterbury. Recently, Condron *et al.* (1996) using three of these soils where phosphorous was examined in more detail by ^{31}P-nuclear magnetic resonance and soil P fractionation, found that conifers enhanced mineralisation of labile (and to a lesser extent more resistant) forms of soil organic P. The study described here examines the magnitude and distribution of apparent effects of conifer plantations on topsoil inorganic phosphorus in a much larger range of eastern South Island high country grasslands.

For about 1000 years the formerly wooded montane zone of the Canterbury Region, generally 400-1000 m a.s.l., has been occupied by grasslands (Molloy, 1969). During the last 150 years, these grasslands have been used for extensive pastoral farming, in which burning and grazing transformed to short grasslands the tall tussock grasslands, often *Chionochloa rubra* (red tussock) in the montane zone. In more recent years, the increase of *Hieracium* species has signalled alarming deterioration in grassland condition (Martin *et al.*, 1994). Following pastoral settlement, numerous small plantations of introduced conifers were established for livestock shelter, farm timber requirements, and as an amenity for homesteads. Early in the 20th century, lessees taking up pastoral land derived by partition of the earlier, larger runs, were required to make tree plantings as a condition of their leases. From the 1950s, experimental revegetation plantings with conifers and some other mountain species were established on earlier deforested montane and subalpine sites, initially for land protection (Ledgard, 1993). In recent years interest has quickened in conifer forests as a basis for or important contributor to sustainable land use of montane grassland terrain, now often in degraded condition (Belton, 1991, 1992; Ledgard, 1993).

The forest topsoils analysed in this study were sampled during the survey of exotic conifer plantations in the Canterbury high country of Ledgard & Belton (1985). In that survey, soils were examined along with other site factors, in an attempt to account for any variation in tree growth between sites. The soil samples were analysed for inorganic P extracted by 0.5 *M* H_2SO_4, total N and pH (Blakemore *et al.*, 1972). No site factor other than precipitation contributed significantly to the variation in forest growth (Ledgard & Belton, 1985). They noted that these soil samples had inorganic phosphorus levels which were very high by New Zealand Soil Bureau ratings (Miller, 1968) for the principal soil groups of the high country grasslands (brown-grey earths, yellow-grey earths, high country yellow-brown earths and recent soils). We had little information on the possible significance of such topsoil reserves of phosphate (Miller, 1968) to the availability of P in forested soils. Our initial comparative testing of forested and grassland soils for available P (0.5 h Olsen-P) was summarily reported (Belton *et al.* 1990, O'Connor, 1986) but no proper explanation of these results could be attempted before the reporting of more thorough comparative testing of a limited range of sites by Davis & Lang (1991).

METHODS

The present study began as a comparison of forest topsoil 0.5 *M* H_2SO_4-P before ignition (inorganic P), total nitrogen (N) and pH data with equivalent records from unimproved grasslands in the same geographic zone. The forest soil samples had been taken from mensuration plots located within mature, fully-stocked stands of one of five conifer species: *Pinus nigra, P. ponderosa, P. radiata, Larix decidua* or *Pseudotsuga menziesii.* The plantations ranged in age from 20 to 67 years, with a mean age of 46 years. Each soil sample was a composite of eight cores, 25 mm diameter, 150 mm deep, taken from the mineral A horizon at randomly chosen midpoints between trees within the plots. Soil samples were excluded from later analysis if there was any indication of contamination of the forest stands by livestock or fertiliser topdressing. The soils were ascribed to soil sets in the field from examination of soil profile characteristics and identification of landform type (Ledgard & Belton, 1985). The laboratory methods used there are described by Ledgard & Belton (1985), following Blakemore *et al.* (1972).

To compare forested soil data for inorganic P, total N and pH with accessible data from comparable unimproved grasslands in the same geographic range, all published data and some unpublished records from the high country from North Canterbury to North Otago were gathered and sorted into genetic soil groups, as shown in Table 1. The sources of these records are indicated in Appendix 1. Records were not included from steepland sites, from the subalpine zone, or from soils of dominantly schist parent material. As it was not possible for some of the earlier grassland records to ascribe these records to soil sets (New Zealand Soil Bureau, 1968), the comparison for these properties between forest and unimproved grassland sites was therefore made at the moisture-classified soil group level.

After analysis of the conifer plantation samples for H_2SO_4-P, total N and pH at the New Zealand Forest Research Institute (NZFRI) laboratories, sufficient air dried soil was available for further analysis from 109 of the original 123 samples. Sixteen of these remaining samples, selected at random, were analysed again for 0.5 M H_2SO_4-P at Soil Bureau, Department of Scientific and Industrial Research (DSIR), to confirm the NZFRI results. The remaining 93 samples were then sent to the Ministry of Agriculture and Fisheries (MAF) Laboratory, Invermay, for the routine 0.5 h Olsen-P test (Grigg, 1965). This test of "readily available" phosphorus was chosen because it is widely used for advisory work in pastoral agriculture (Cornforth & Sinclair, 1984). It has been used sometimes in forestry in New Zealand (Ballard, 1970) and in Europe (Harrison, 1989).

Of the 93 conifer plantation samples tested for Olsen-P, 77 belonged to one or other of 11 South Island high country soil sets (New Zealand Soil Bureau 1968). These soil sets were used as the framework for comparison of Olsen-P levels under grassland and forest. Grassland 0.5 h Olsen-P data for the same 11 soil sets were obtained from some DSIR records, from recent research projects of Lincoln University (then Lincoln College), from MAF Tara Hills Research Station at Omarama, and from MAF Advisory records.

Annual precipitation estimates for each grassland site were obtained where possible from the isohyet map in Belton & Ledgard (1984).

In order to compare any alteration in Olsen-P under plantation forestry influence with outcomes from agricultural development involving phosphatic fertiliser, we used supplementary information on vegetation and fertiliser practice, to sort the grassland soil data into the following three "grassland improvement" classes

Unimproved grassland: Tussock and other native or adventive grasses with little or no legume component, and excluding all sites previously topdressed with superphosphate fertiliser (91 records).

Semi-improved grassland: Grasslands previously topdressed, with some clover or other legume presence associated with grasses such as fescue tussock (*Festuca novae zealandiae),* browntop *(Agrostis capillaris),* sweet vernal (*Anthoxanthum odoratum)* and Yorkshire fog (*Holcus lanatus)*, but excluding grassland composed substantially of legumes, ryegrass (*Lolium perenne)* and cocksfoot (*Dactylis glomerata*) (84 records).

Improved pasture: Grasslands which had been oversown and regularly topdressed with fertiliser, principally composed of legumes such as white clover (*Trifolium repens*) and high fertility grasses such as ryegrass (*L. perenne*), cocksfoot (*D. glomerata*) and *Poa pratensis* (85 records).

The grassland soil samples for Olsen-P had usually been taken from a depth of 0-100 mm, shallower than the samples of topsoil under forest (0-150 mm). In addition to the comparisons in these limited chemical properties of soils under differently developed grasslands and conifer plantations, we also took the opportunity to examine the relationships within the conifer samples of Olsen-P, inorganic P, pH and precipitation.

RESULTS

Values for phosphorus extractable in 0.5 *M* H_2SO_4 obtained at the Soil Bureau laboratory were in close agreement with values obtained at NZFRI laboratory for the same 16 samples (r=0.987***).

Relationships within conifer plantation samples

Examination of relationships within plantation samples showed no correlation of pH with Olsen-P, inorganic P or precipitation. There was some correlation between inorganic P and precipitation (r=0.359*, n=93), and a highly significant correlation between Olsen-P and inorganic P across all soils (r=0.685**, n=93). Similar correlations were obtained for the drier soils, brown-grey earths, yellow-grey earths and dry-hygrous high country yellow-brown earths considered together (r=0.892**, n=38), and for the youthful and recent soils on loess or alluvium (r=0.933**, n=25) but not for hygrous high country yellow brown earths.

Total N, pH and inorganic P under grasslands and conifers

Total N, pH and inorganic P values for 123 forest topsoil samples and for 102 topsoil samples taken from unimproved grasslands (see Appendix 1) are presented as means with standard deviations for the main soil groups in Table 1. Coefficients of variation are also presented for each of the inorganic P values, to be compared later with variability in Olsen-P values. For all of the soil groups, and especially the high country yellow-brown earths, mean levels of topsoil inorganic P were higher under conifer plantations than under unimproved grasslands. Imbalance in cell size prevented satisfactory statistical comparisons for each soil group and our inability to ascribe all earlier grassland records to particular soil sets prevented us from making the comparison of conifers and grasslands on any more detailed basis than that shown in Table 1.

The first four soil groups of Table 1 represent a gradient of increasing soil moisture. Topsoil pH values under grassland decline with increasing soil moisture class from the brown-grey earths in semi-arid climate to the hygrous high country yellow-brown earths in humid climate. Conifer plantations have more uniform and lower pH values than the grasslands. In the driest soil groups (brown-grey earths and yellow-grey earths) and in the youthful soils on loess, topsoil pH under conifers is clearly lower than under grassland. Associated with such marked pH reduction is an increase in soil mean N.

Olsen-P under grasslands and conifers

Soil set was the only selection criterion applied to the grassland soil sample records to allow comparisons of vegetation effects on Olsen-P to be made. The 11 soil sets in the comparison of conifer plantations with three grassland improvement classes are shown in Table 2, the sets being arranged within the groups by the then current New Zealand soil classification (New Zealand Soil Bureau, 1968). Within each soil set, Olsen-P values for topsoils under conifer plantations are generally 2 to 4 times greater than the grassland topsoil values.

From Table 2 it can be seen that the standard deviations for Olsen-P values from grassland and conifer topsoils are far from equal among all cells, ranging up to 37.2 under conifers on the youthful Mesopotamia soil. For valid statistical comparisons to be made with data of this type, it is necessary to transform the raw data so that variance becomes independent of the mean, i.e. the amount of variation ***does not*** depend on the magnitude of the mean value. This point is well made by Draper & Smith (1981, sec.1.4) in an examination of the assumptions underlying regression analysis. The choice of transformation is a vexed question, the logarithm or square root commonly being used. Methodology to assist in the appropriate choice of transformation is given by Velleman & Hoaglin (1981, p.49) using a ladder of powers. Using this technique with the data from Table 2, we found that the standard deviations were closest to each other when the logarithm was used.

Table 3 presents results of analysis of variance for the four vegetation classes and six soil groups, using the log-transformed Olsen-P values. Significant differences occur between conifers and grasslands, but not between levels of grassland development. Brown-grey earths differ significantly from the yellow-brown earth groups, and youthful soils on loess also differ significantly from some other soil groups, but these differences are small in comparison with the difference between forest and grassland, shown overall and also clearly demonstrated within each soil group. The interaction between vegetation class and soil group was not significant, indicating that when variance was reduced by logarithmic transformation, conifer plantations had similar Olsen-P effects for all soil groups.

The earlier comparison (Table 1) of inorganic phosphorus extracted in 0.5 *M* H_2SO_4 suggested that the difference between grassland and conifer forest was more clearly demonstrated in the soil groups (HCYBEs) at the wetter end of the moisture gradient. To determine whether the difference between conifer plantation and grassland soils in Olsen-P was affected by the moisture status of the site, a further analysis was carried out of the relationship between Olsen-P values and annual precipitation, where this last value was known with confidence. Data before transformation from 294 of the 337 sites are plotted in Figure 1, with a calculated linear regression line superimposed for each of the three grassland development classes and for conifer forest plantations. Figure 2 summarily presents the regressions of the log-transformed Olsen-P data against precipitation, for a single amalgamated grassland class and for conifer forest, showing confidence intervals. The enhancement of Olsen-P levels from afforestation is shown to be of similar magnitude over the precipitation range of the survey with similar decline in Olsen-P with increasing precipitation, under both forest and grassland.

We could detect no relationship between forest plantation age and either Olsen-P or inorganic P, within the conifer soil samples, nor could we discern any apparent effect of conifer species. We conclude from this survey, therefore, that for plantations of 20 years age or more, the enhancement of either phosphorus value above the level of grassland topsoils is independent of plantation age or species composition.

DISCUSSION

Perhaps one of the earliest observations recorded in New Zealand of soil fertility enhancement by conifers was made by A.H.Cockayne, one of the founders of scientific agriculture in New Zealand, at Otekaieke in the Lower Waitaki Valley (Cockayne, 1914). Land used for horticulture following removal of a *Pinus radiata* plantation from part of the area, demonstrated clearly enhanced productivity in crops sown on the previously wooded portion. More recent evidence of enhanced productivity following conifers in the Canterbury high country has been provided by Ledgard & Baker (1982), Belton (1992), and Davis & Lang (1991). Davis & Lang used more intensive soil analyses on a limited number of sites, where they compared adjoining grasslands and plantations. There was marked variation among sites in their results. Their results have greatly aided the interpretation of the current work, in which a very limited set of analyses was done on a much larger conifer plantation topsoil collection with a search of published and accessible records from comparable grassland topsoils. Issues warranting some discussion here include the distribution and magnitude of conifer effects on topsoil phosphorus and possible processes involved in the apparent increase in topsoil phosphorus under plantation forests.

Relationship of conifer effects on inorganic phosphorus to other soil changes

Our examination in Table 1 of the accessible records of high country grassland topsoil values for pH, total N, and inorganic P indicated that soil groups with naturally higher levels of inorganic P (brown-grey earths, yellow-grey earths, and youthful yellow-brown earths on loess) had the largest pH depressions and greatest N increases attributable to conifer plantations. We presume that these N and pH changes were associated with increases in topsoil carbon under conifer plantations (cf Davis & Lang, 1991). These same more fertile soil groups also demonstrated least proportional increases (group means 16 to 40 percent) in inorganic P associated with conifer plantations, compared with the other soil groups in Table 1 (group means 70 to 140 percent increase in inorganic P). As has been noted earlier, the variation in these survey and historical record data is high and some caution is needed in inferring differences between soil groups in their reaction to conifer plantations. Davis & Lang (1991) found that appreciable pH decline under conifers, associated with increase in organic carbon, often with some increase in total nitrogen, occurred only on their drier sites in the Mackenzie Basin. None of these drier sites is ascribed to any of the three soil groups (BGEs, YGEs, or youthful HCYBEs on loess) identified in the present paper as those most clearly indicating N and pH changes from conifers. It is noteworthy, however, that in the Davis & Lang study, the sites which showed the most dramatic increase in topsoil inorganic P and even slight increases in total P, were their sites 6 and 7, ascribed to the Mackenzie soil set within the dry-hygrous HCYBE group. This same soil group is also identified in Table 1 of the present paper as that with the largest proportional increase from grassland to conifer plantation in inorganic P. In the Davis & Lang study, the five central Canterbury sites, which all belong to the hygrous HCYBE group, all show smaller increases in inorganic P from grassland to conifer plantation, as do soils of the same group in the present paper. This increase in inorganic P in the hygrous HCYBE soils in the Davis & Lang study was accompanied by a small general decrease in total topsoil P from grassland to plantation. Almost all sites exhibited a decrease from grassland to conifer plantation in organic P. Mean values given for grassland were 50 mg/100 g (s.e. 9.1) and for conifer plantations 40 mg/100 g (s.e. 8.8). Individual site values were not presented for organic P but it can be inferred from comparison of their graphs for total P and inorganic P that in the hygrous HCYBEs from central Canterbury, the decrease in organic P from grassland to conifer plantation was from about 650 mg per kg down to about 520 mg per kg. As a percentage of total P this decline was from about 70 per cent to little more than 60 per cent. In the dry hygrous sites in the

Mackenzie, the deduced net change in organic P appears to have been much less, from about 260 mg per kg down to about 230 mg per kg.

These comments reinforce the inference by Davis & Lang (1991), following the conclusions of Fisher & Stone (1969), of substantial net mineralisation of residual grassland organic matter during occupancy by conifers. The suggestion was made by Davis & Lang that other mechanisms, such as exploitation of nutrients in deeper soil layers, might be invoked to account for their results from the Mackenzie Basin dry-hygrous soils. They noted that stand age and drier soils were confounded in their Mackenzie sites. Our own present analysis failed to discover any influence of stand age, perhaps because no sites were included in the Ledgard & Belton (1985) survey that had stands younger than 20 years. Our own more recent limited and unpublished observations of younger stands have revealed clearcut enhancement of productivity of resident herbaceous vegetation close to planted conifers, without demonstrating significant differences in topsoil Olsen-P values. Like Davis & Lang (1991) in their comparison of grassland and conifer stands in central Canterbury, Fisher & Stone (1969) concentrated their comparative studies in New York State on young (10 to 14 years) conifer plantings. They noted the "eruptive nature of such changes" in HF-extractable organic N, available N and extractable P in topsoils in such conifer plantings in contrast to surrounding old field vegetation, and they also recorded that such differences were not apparent with 32 and 33 year old stands. Our suggestion is that the phenomenon of Olsen-P enhancement by conifer plantations, as recorded in Mackenzie Basin sites by Davis & Lang (1991) and demonstrated for the ***whole scope of our present survey***, belongs principally to older conifer stands. Hawke & O'Connor (1993) indicate from their studies at Tikitere that such a phenomena may be evident in stands as young as 13 years.

Sources of variability and pattern in Olsen-P in grassland and plantation

The feature which calls for some comment is the variability in Olsen-P results, along with the underlying order that can be discerned in them. Whereas coefficients of variation in inorganic P were, for most soil groups, much less for conifer plantation collections than for unimproved grassland records (Table 1), Olsen-P values showed high coefficients of variation under conifers and under unimproved grasslands, for several soil groups (Table 2). We interpret from the correlation of Olsen-P values with inorganic P values in the conifer plantation samples (r=0.685**) that almost half of the variation in Olsen-P is associated with variation in inorganic P, itself pedogenetically influenced by precipitation, topsoils of the drier soil groups tending to have higher levels of inorganic P. Following Harrison's (1989, p.48) comments in his review of phosphorus distribution and cycling in European forests, we recognise bicarbonate-extracted Olsen-P as "labile inorganic and organic P". We believe that a substantial proportion of the variation in Olsen-P of grassland and forest samples will arise from variability in the vitality of the soil organic system. In soils under grassland, earlier soil microbiological studies have given some indication of the variation in soil biological activity in the montane zone (e.g. O'Connor, 1982). In recent years, modelling and empirical research have together sketched out the substantial influence of livestock behaviour on nutrient cycling in montane grasslands (O'Connor, 1983; Allan, 1985; Thorrold *et al.*, 1985; O'Connor & Harris, 1992). We suspect that the uneven distribution of animal returns may contribute to high variability in grassland Olsen-P values and to the failure of our survey to demonstrate significant differences between grassland development classes. The integrated dynamics of P cycling with the cycling of C, N, and S have now become a feature of international grassland research (Parton *et al.*, 1988). Research is lacking, however, to demonstrate variability in soil biological activity in montane soils under conifer plantations in New Zealand, despite the significance of New Zealand contributions to the understanding of the soil biology and biochemistry of phosphorus in other ecosystems (e.g. Tate, 1984). From reviews of different aspects of phosphorus cycling in forests in Europe and North America (Stevenson, 1986; Cole & Sanford, 1989; Harrison, 1989; Binkley, 1994), we expect that further research would reveal profound changes in soil biological conditions as a grassland soil system is replaced with a coniferous forest system.

In their paired site comparisons, Davis & Lang (1991) recorded that proportional increases in Olsen-P from grassland to conifer plantation were greater in the Mackenzie Basin sites (2.7 to 8.4 fold) than in the central Canterbury sites (0.8 to 2.3 fold). From their central Canterbury sites, Olsen-P levels in conifer plantation topsoils seldom exceeded 10 ppm, scarcely reaching one per cent of total phosphorus. Their Mackenzie Basin conifer samples showed Olsen-P values comparable with those of the present paper. Does this represent a regional or soil group difference in conifer plantation influence? or is the difference attributable simply to such a factor as a difference in ages of conifer stands? For most of the soil sets in Table 2, the mean increase from grassland to conifer plantation in Olsen-P was from two-fold to four-fold. For soil groups, the mean increase in Olsen-P from grassland to conifer plantation ranged from 2.0-fold for brown-grey earths to 3.7-fold for yellow-grey earths. Analysis of variance of the transformed values found no significant interaction of soil group and vegetation, indicating that enhancement of Olsen-P under conifers was similar for all soil groups. Likewise, the closely similar slope of regression lines in Figure 2 showed the similarity of influence of increasing precipitation on transformed Olsen-P values, regardless of vegetation.

Sparling *et al.* (1985) have demonstrated the substantial enhancement of Olsen-P extraction by air drying of pasture topsoil samples before analysis. Their data from concomitant effects of air drying on biomass carbon and from increase in inorganic P after fumigation of moist soil, led them to suggest that the enhanced Olsen-P in the dried soils could be accounted for almost entirely by the release of P from the killed cells. In their view, their "findings cast doubt on the reliability of 'plant available' P measurements made on air-dry soils, because it is not known to what extent the microbial biomass P of fresh soils can be regarded as being plant-available". They identified soils where microbial biomass P was likely to be important as soils with organic C content of > 2 per cent, predominantly under permanent pasture, having $NaHCO_3$-extractable P values < 20 ppm, and not being subject to extreme moisture deficits. Their soil criteria suggest we should be wary of the influence of microbial biomass P in elevating Olsen-P values in air-dried samples of hygrous HCYBEs in particular. We emphasise, however, that the important phenomenon in our data is the substantial margin by which the conifer plantation values exceed the grassland values for comparable soils. The influence of drying on release of nutrients from soil biomass has been noted as a widespread field and laboratory phenomenon for many years (Birch, 1958). We have no reason to suppose that such an effect would artificially induce higher values in forest samples.

Possible processes of mineral phosphorus enhancement

Davis & Lang (1991) and Condron *et al.*(1996) have produced persuasive evidence of increased mineralisation of organic matter residual from grasslands in young conifer stands planted there. In this they support the findings of Fisher & Stone (1969). Is their some further process involved in older stands? From the regression demonstrated in Figure 2, and making use of background soil data from studies referred to in Appendix 1, including data of Davis & Lang (1991), we estimate a steady trend in Olsen-P values under conifers from about 7 percent of total topsoil phosphorus in the driest soils of our survey (about 50 mg per kg of 700 mg per kg, with about one third of total P as organic) to about 2 or 3 percent of total topsoil phosphorus at the wetter end of our sampling range (about 20 mg per kg of 900 mg per kg, with about two thirds of total P as organic). Again we emphasise that for the plantation samples at the wetter end of our sampling range, the mean Olsen-P values were several times greater than those from the much younger plantations in central Canterbury, studied by Davis & Lang (1991). Whether the general phenomenon of enhanced Olsen-P which we associate with mature plantations has involved "nutrient pumping" from deeper soil layers, as was earlier suggested (O'Connor, 1986), we cannot fairly conclude from our data. Davis & Lang (1991) pointed to the possible relevance of this phenomenon to the dry-hygrous Mackenzie sites of their study. The substantial increase in inorganic P recorded for hygrous soils in Table 1, may be outweighed by a decrease in organic P, but this issue must await an extension of the thorough analyses of Davis & Lang (1991) to a wider range of paired sites.

CONCLUSION

Regardless of the further scientific explanations which must be awaited, the practical significance of the present findings cannot easily be avoided. Because a substantial proportion of the greatly enhanced labile P of long established plantations seems to be associated with higher phosphorus accumulation into the organic regime and subsequent mineralisation, we interpret the Olsen-P enhancement as an indicator of generally enhanced "soil fertility" for associated or subsequent vegetation. This is consistent with the observations reported on herbaceous vegetation subsequent to conifer plantations of some maturity. Nutrient balances have been shown to be significant in the high country to the sustainability of the natural grasslands (Williams *et al.*, 1977, 1978), to the sustainability of pastoral uses (O'Connor & Harris, 1992), and to the sustainability of forest uses (Nordmeyer *et al.* 1987; Belton, 1992). In view of the apparently substantial forest influence here unfolded, it would seem imperative that local and regional landscape understanding of nutrient fluxes and balances should become the technical basis for any long term planning of mountain land use, including the spatial or temporal separation or integration of land uses. This would require a substantial reorientation of national research priorities for this troublesome region.

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Appendix 1: Sources of data for N, P, and pH for topsoils samples from unimproved grasslands, as summarised in Table 1.

All available published and some unpublished records from the greater Canterbury Region were searched for results of analysis for pH, N and inorganic P, where these had been carried out on samples from the same topsoils. Records were not used where they were from steepland soils, soils of the subalpine zone, or soils derived from schist parent material. These exclusions were made as beyond the geographic range of the soils sampled in the forest survey. The sources of sample records in each of the genetic soil groups are identified by a number corresponding to the numerical source reference list which follows. Where there is a predominant source for any soil group the number is underruled.

Soil Group	Sources
Brown grey earths	4, 6, 8, 10
Yellow grey earths	2, 4, 6, 10
Dry hygrous yellow brown earths	1, 3, 4, 5, 6, 7, 10
Hygrous yellow brown earths	4, 5, 6, 9
Youthful soils from loess	1, 4, 5
Recent soils from alluvium	1, 9

Some clarification is needed of the relationship of P (extracted by 0.5 *M* H_2SO_4 from unignited soil) and P_i (inorganic phosphorus). Walker & Adams (1958, 1959) reported their results as P_t (total P) and P_o (organic P) or as P_i and P_o. where P_i=P_t-P_o., where P_o had been determined by difference between 0.5 *M* H_2SO_4-extracted P of ignited and unignited soil, and P_t had been determined by 0.5 *M* H_2SO_4 extract of ignited soil (Walker & Adams, 1958) or by acid digestion using HF-HNO_3 (Walker & Adams, 1959). For weakly or moderately weathered soils as are included in the present report, their studies showed results for P_t to be similar by the two methods. In the present report, their reported or calculated values for P_i have been used for inorganic P even though these may sometimes represent a slight overestimate of what would have been determined by extraction with 0.5 *M* H_2SO_4. This last method is that used in all other sources and in the survey of forest plantations.

Depths of topsoil samples varies from 7.5 cm to as much as 17.5 cm, according to horizon depth and method of sampling. Where necessary, analytical results have been recalculated from those for two A horizons to give values for either 0-10 cm or 0-15 cm samples.

Sites sampled by Walker & Adams (1958, 1959) and by Thapa (1956) have been located with the help of A.F.R. Adams and their general soil classification revised in keeping with other later studies. Published reports from North Otago (McIntosh *et al.*, 1981) have been supplemented by data for individual sample sites as pers. comm. from P.D. McIntosh. Unpublished Lincoln University analytical records from Department of Soil Science and the former Tussock Grassland and Mountain Land Institute have been collated by Dr P.J. Tonkin and K.F. O'Connor respectively. Unpublished New Zealand Soil Bureau analytical records have been made available by Dr R.L. Parfitt and L.C. Blakemore.

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Figure Captions

Fig 1. Relationship between Olsen-P (ppm) and precipitation (cm) for soils from unimproved grassland, semi-improved grassland, improved pasture and conifer forest.

Fig 2. Relationship between logarithmic transformed Olsen-P and precipitation (cm) for soils from aggregated grasslands and pasture (lower curve) and forest (upper curve) with 95% confidence limits on each relationship.

$$y \text{ (grassland)} = 3.197 - 0.00746x$$
$$y \text{ (forest)} = 4.158 - 0.00703x$$

Table 1: Soil group means and standard deviations for total Nitrogen, pH (H_2O) and phosphorus, together with C.V. for phosphorus, extracted in 0.5 *M* H_2SO_4 from topsoils under unimproved grasslands[1] and under conifer plantations for topsoils of the same geographic range.

Soil group	Under grasslands					Under conifers				
	n	Total N%	pH(H_2O)	0.5 *M* H_2SO_4-P ug/g		n	Total N%	pH(H_2O)	0.5 *M* H_2SO_4-P ug/g	
				$\bar{x}$ ± s.d.	CV%				$\bar{x}$ ± s.d.	CV%
Brown-grey earths	4	0.25±0.131	6.1±0.08	412±295.9	71.8	8	0.33±0.143	5.3±0.26	478±134.8	28.2
Yellow-grey earths	47	0.24±0.072	6.2±0.13	339±101.0	29.8	4	0.30±0.134	5.2±0.19	475±68.1	14.3
Dry-hygrous high country yellow-brown earths	27	0.33±0.061	5.6±0.25	198±111.8	56.5	40	0.32±0.71	5.3±0.27	472±142.1	30.1
Hygrous high country yellow-brown earths	16	0.37±0.110	5.4±0.24	201±114.7	57.1	29	0.40±0.120	5.2±0.28	349±147.0	42.1
Youthful yellow-brown earths on loess	3	0.18±0.035	5.9±0.12	394±223.2	56.6	24	0.38±0.110	5.2±0.36	556±205.6	37.0
Recent soils on alluvium	5	0.33±0.136	5.7±0.29	257±82.3	32.0	18	0.32±0.108	5.6±0.32	451±164.7	36.5
	102					123				

[1]Sources are identified in Appendix 1.

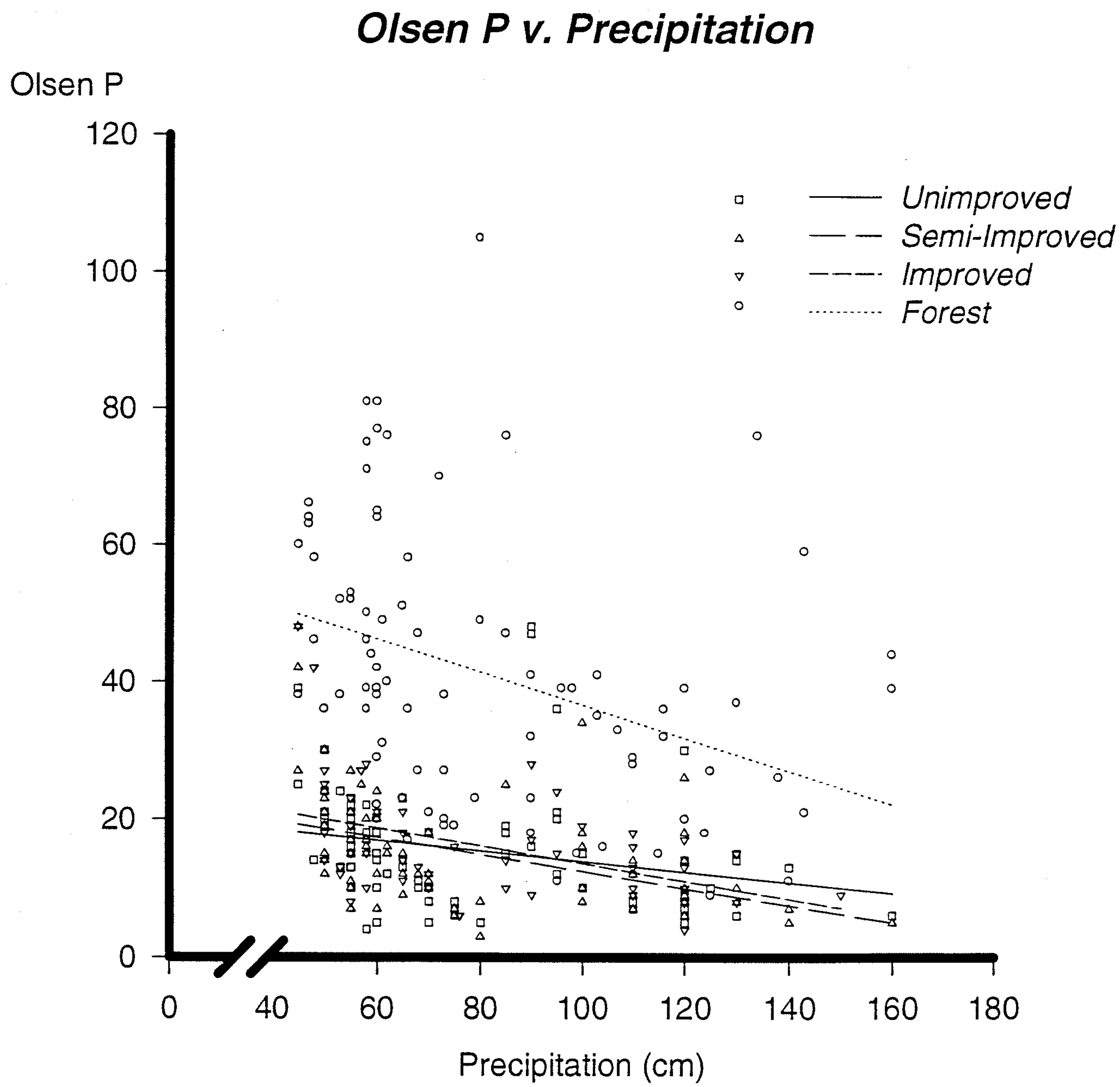
Table 2: 0.5 h Olsen phosphorus values arranged by soil sets within soil groups for topsoils under grasslands at different stages of agricultural development and under conifer forest plantations.

Number of samples (n), sample mean (x) and standard deviation (sd) for soil sets and soil group coefficients of variation (c.v.) for unimproved grasslands and conifer forests.

		Unimproved grassland	CV %	Semi-improved grassland	Improved pasture	Conifer forest	CV %
Brown-grey earths							
Grampians	n	6		8	6	5	
	x	22.3		27.5	29.7	54.0	
	sd	9.95	44.6	12.52	12.96	18.23	33.8
Yellow-grey earths							
Meyer	n	6		4	0	4	
	x	15.2		14.5	-	55.0	
	sd	7.08	46.6	7.94	-	15.19	27.6
Dry hygrous high country yellow-brown earths							
Mackenzie	n	16		16	12	5	
	x	16.1		14.4	14.9	49.4	
	sd	6.20		4.87	4.06	13.90	
Dalgety	n	5		8	9	3	
	x	15.2		10.0	13.4	50.3	
	sd	6.57		6.26	4.75	3.79	
Pukaki	n	6		9	4	8	
	x	11.5		15.0	18.8	33.5	
	sd	3.39		6.63	10.11	20.00	
Tekapo	n	6		6	2	12	
	x	5.5		11.2	11.0	49.7	
	sd	3.56		2.93	7.07	27.04	
Ohau	n	6		2	0	1	
	x	5.2		7.0	-	23.0	
	sd	3.25	43.1	1.41	-	-	46.9
Hygrous high country yellow-grown earths							
Craigieburn	n	14		11	20	3	
	x	10.7		11.1	14.4	18.3	
	sd	4.81		5.82	6.07	9.45	
Cass	n	12		5	6	11	
	x	13.7		17.6	10.8	31.4	
	sd	4.05	37.1	5.18	8.64	10.96	37.2
Youthful yellow-brown earths on loess							
Mesopotamia	n	10		11	12	11	
	x	28.3		11.3	19.7	54.7	
	sd	15.20	53.7	5.88	6.04	37.21	68.0
Recent soils on alluvium							
Tasman	n	4		4	14	14	
	x	15.3		5.8	18.9	34.1	
	sd	4.11	26.9	1.50	8.49	20.50	60.1

Table 3: Number (n), means (x) and standard deviation (sd) for log-transformations of Olsen-P values for soil groups under different vegetation classes, together with adjusted means and standard errors for soil groups and for vegetation classes to allow for cell size differences.

SOIL GROUPS		VEGETATION CLASS Unimproved grassland	Semi-improved grassland	Improved pasture	Conifer forest	Adjusted means and s.e.
Brown-grey earths	n	6	8	6	5	
	x	3.0193	3.1257	3.3040	3.9428	3.395
	sd	0.4672	0.4895	0.4673	0.3351	0.11051
Yellow-grey earths	n	6	4	0	4	
	x	2.5990	2.5529		3.9757	2.993
	sd	0.5802	0.5772		0.2977	0.14870
Dry-hygrous high country	n	39	41	27	29	
Yellow-brown earths	x	2.2582	2.4464	2.6172	3.6596	2.738
	sd	0.7558	0.4872	0.3882	0.5507	0.04765
Hygrous high country	n	26	16	26	14	
Yellow-brown earths	x	2.4136	2.4633	2.4577	3.2570	2.651
	sd	0.4125	0.4935	0.6029	0.4788	0.06150
Youthful yellow-brown	n	10	11	12	11	
soils on loess	x	3.2009	2.3312	2.9355	3.8394	3.066
	sd	0.5719	0.4150	0.3086	0.5736	0.08323
Recent soils on alluvium	n	4	4	14	14	
	x	2.6947	1.7269	2.8059	3.3569	2.702
	sd	0.2890	0.2350	0.5874	0.6191	0.09358
All soil groups	n	91	84	85	77	
	x	2.4980	2.4786	2.6929	3.5919	
	sd	0.6762	0.5447	0.5384	0.5714	
Adjusted means and se	x	2.615	2.565	2.819	3.698	
	se	0.06367	0.06607	0.06661	0.06690	


Olsen P v. Precipitation
Olsen P
120
100
80
60
40
20
0
Unimproved
Semi-Improved
Improved
Forest
0
40
60
80
100
120
140
160
180
Precipitation (cm)

Log (Olsen P) v. Precipitation