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

M. C. BELTON

Ministry of Forestry, P.O. Box 25-022, Christchurch, New Zealand

K. F. O'CONNOR

Centre for Mountain Studies, P.O. Box 84,
Lincoln University, Canterbury, New Zealand

and A. B. ROBSON*

Centre for Computing and Biometrics, P.O. Box 84,
Lincoln University, Canterbury, New Zealand

(Received for publication 23 December 1994; 23 August 1996)

ABSTRACT

Topsoils under planted conifer forests in the Canterbury high country have high levels of 0.5 M H_2SO_4-P (inorganic phosphorus) compared to published records from topsoils of grasslands on soils of the same high country soil groups. Group means under conifers were from 16% to 140% 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-phosphorus 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 phosphorus and Olsen-phosphorus 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-phosphorus values with increasing precipitation. For most soil taxa, variability in Olsen-phosphorus was high under any vegetation cover, but Olsen-phosphorus was clearly greater under conifer plantation than under grassland. Soils from the three development classes of grassland had similar mean Olsen-phosphorus levels whereas the average forest Olsen-phosphorus levels were generally 2 to 4 times higher than the average grassland level for the corresponding soil.

There was 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 appeared to be of similar magnitude along the whole precipitation range sampled, a situation apparently different from that outlined for "inorganic phosphorus".

Keywords: high country; conifers; soil phosphorus; soil fertility; mineralisation.

---

* Author to whom correspondence should be addressed.

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 the effects of particular tree species on soils has been compiled by Binkley (1995). 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 phosphorus (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 nitrogen and phosphorus mineralisation or other extraction from organic matter apparently residual from the successional vegetation. Later, Fisher (1990) reviewed evidence for 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. This was followed by a detailed study of the forms of phosphorus in soils of three of their sites (Condron *et al.* 1996).

The study described here examined the magnitude and distribution of apparent effects of conifer plantations on topsoil 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* Zotov (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). After 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 twentieth 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 by Ledgard & Belton (1985) of exotic conifer plantations in the Canterbury high country. 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 phosphorus extracted by 0.5 M H_2SO_4, total nitrogen, 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). Miller (1968) had suggested that 0.5 *M* H_2SO_4-P gave a measure of the reserve of phosphates in the soil. We had little information on the possible significance of such topsoil reserves of phosphate to the availability of phosphorus in forested soils.

In this study we wished to compare the available and total phosphorus status of forested and grassland sites across the whole geographical range of the Canterbury high country plantations surveyed by Ledgard & Belton (1985).

We chose the Olsen test to facilitate comparison of available phosphorus in forest samples with a much larger number of existing grassland data. This test of "readily available" phosphorus is widely used for advisory work in pastoral agriculture (Cornforth & Sinclair 1984) and has been used in forestry in New Zealand (Ballard 1970) and in Europe (Harrison 1989). Our initial comparative testing of forested and grassland soils for available phosphorus (0.5 h Olsen-phosphorus) 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) and further soil analysis by Condron *et al.* (1996).

METHODS

The present study began as a comparison of forest topsoil characteristics 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* Arn., *P. ponderosa* P.Laws. et Laws., *P. radiata* D. Don, *Larix decidua* Mill., or *Pseudotsuga menziesii* (Mirb.) Franco. 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). Samples were analysed for 0.5 *M* H_2SO_4-extractable phosphorus before ignition (inorganic phosphorus, P_i), total nitrogen, and pH using methods described by Ledgard & Belton (1985), following Blakemore *et al.* (1972).

To compare forested soil data for inorganic phosphorus, total nitrogen, 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 (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 1968a), the comparison for these properties between forest and unimproved grassland sites was therefore made at the moisture-classified soil group or sub-group level (Taylor & Pohlen 1962), hereinafter referred to as soil groups.

TABLE 1–Soil group means and standard deviations for total nitrogen, pH (H_2O), and phosphorus, together with coefficient of variation for phosphorus, extracted in 0.5 *M* H_2SO_4 from topsoils under unimproved grasslands* 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 (μg/g) x̄ ±s.d.	CV%	n	Total N (%)	pH(H_2O)	0.5 *M* H_2SO_4-P (μg/g) x̄ ±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±0.071	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				

*Sources are identified in Appendix 1.

After analysis of the conifer plantation samples for H_2SO_4-P, total nitrogen, and pH at the New Zealand Forest Research Institute (NZ FRI) 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 NZ FRI 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-phosphorus test (Grigg 1965).

Of the 93 conifer plantation samples tested for Olsen-phosphorus, 77 belonged to one or other of 11 South Island high country soil sets (New Zealand Soil Bureau 1968a). These soil sets were used as the framework for comparison of Olsen-phosphorus levels under grassland and forest. Grassland 0.5 h Olsen-phosphorus 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 by Belton & Ledgard (1984).

In order to compare any alteration in Olsen-phosphorus 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-zelandiae* (Hack.) Ckn.), browntop (*Agrostis capillaris* Sibth.), sweet vernal (*Anthoxanthum odoratum* L.), and Yorkshire fog (*Holcus lanatus* L.), but excluding grassland composed substantially of legumes, ryegrass (*Lolium perenne* L.), and cocksfoot (*Dactylis glomerata* L.) (84 records).

Improved pasture:

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

The grassland soil samples for Olsen-phosphorus 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-phosphorus, inorganic phosphorus, pH, and precipitation. To stabilise variances prior to an analysis of variance the techniques of Velleman & Hoaglin (1981) were used on the Olsen-phosphorus data and the logarithmic transformation chosen. Standard analysis of variance techniques and differences between adjusted means were established using PROC GLM (SAS 1990).

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 NZ FRI 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-phosphorus, inorganic phosphorus, or precipitation. There was some correlation between inorganic phosphorus and precipitation (r=0.359*, n=93), and a highly significant correlation between Olsen-phosphorus and inorganic phosphorus 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 Nitrogen, pH, and Inorganic Phosphorus under Grasslands and Conifers

Total nitrogen, pH, and inorganic phosphorus 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 phosphorus values, to be compared later with variability in Olsen-phosphorus values. For all of the soil groups, and especially the high country yellow-brown earths, mean levels of topsoil inorganic phosphorus were higher under conifer plantations than under unimproved grasslands. Imbalance in cell size prevented satisfactory statistical comparisons within soil groups. Inability to ascribe all early grassland records to particular soil sets precluded more detailed analysis than shown in Table 1.

The first four soil groups of Table 1 represent a gradient of increasing soil moisture. Topsoil pH values under grassland declined 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 had 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 was clearly lower than under grassland. Associated with such marked pH reduction was an increase in soil mean nitrogen.

Olsen-phosphorus 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-phosphorus to be made. The 11 soil sets for which comparisons between conifer plantations and grassland can be made in terms of Olsen-phosphorus are given in Table 2, where the sets are arranged within groups according to the New Zealand soil classification then current (New Zealand Soil Bureau 1968a). Within each soil set, Olsen-phosphorus values for topsoils under conifer plantations were generally 2 to 4 times greater than the grassland topsoil values.

The standard deviations for Olsen-phosphorus values from grassland and conifer topsoils were far from equal among all cells, ranging up to 37.2 under conifers on the youthful

TABLE 2–0.5 h Olsen phosphorus values (μg/g) 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 (CV) for unimproved grasslands and conifer forests.

		Unimproved grassland	CV%	Semi-improved grassland	Improved pasture	Conifer forest	CV%
Sub-xerous 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
Sub-hygrous 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-brown 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

Mesopotamia soil (Table 2). 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. As described in the methods section, we used a logarithmic transformation for this purpose.

Results of analysis of variance for the four vegetation classes and six soil groups, using the log-transformed Olsen-phosphorus values, are presented in Table 3. Significant differences occurred between conifers and grasslands ($p<0.001$), but not between levels of grassland development. Brown-grey earths differed significantly ($p<0.001$) from the yellow-brown earth groups and from recent soils on alluvium. Youthful soils on loess also differed significantly ($p<0.01$) from the yellow-brown earth groups and from recent soils on alluvium. Differences among soil groups were small in comparison with the difference between forest and grassland, shown overall ($p<0.0001$) 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-phosphorus 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 in Olsen-phosphorus between conifer plantation and

TABLE 3—Number (n), means (x), and standard deviation (sd) for log-transformations of Olsen-phosphorus 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 se
Brown-grey earths	n	6	8	6	5	25
	x	3.02	3.13	3.30	3.94	3.40
	sd	0.47	0.49	0.47	0.34	0.110
Yellow-grey earths	n	6	4	0	4	14
	x	2.60	2.55		3.98	2.99
	sd	0.58	0.58		0.30	0.149
Dry-hygrous high country yellow-brown earths	n	39	41	27	29	136
	x	2.26	2.45	2.62	3.66	2.74
	sd	0.76	0.49	0.39	0.55	0.048
Hygrous high country yellow-brown earths	n	26	16	26	14	82
	x	2.41	2.46	2.46	3.26	2.65
	sd	0.41	0.49	0.60	0.48	0.062
Youthful yellow-brown soils on loess	n	10	11	12	11	44
	x	3.20	2.33	2.94	3.84	3.07
	sd	0.57	0.42	0.31	0.57	0.083
Recent soils on alluvium	n	4	4	14	14	36
	x	2.69	1.73	2.81	3.36	2.70
	sd	0.29	0.24	0.59	0.62	0.094
All soil groups	n	91	84	85	77	
	x	2.50	2.48	2.69	3.59	
	sd	0.68	0.55	0.54	0.57	
Adjusted means and se	x	2.62	2.57	2.82	3.70	
	se	0.064	0.066	0.067	0.067	

grassland soils was affected by the moisture status of the site, a further analysis was carried out of the relationship between Olsen-phosphorus values and annual precipitation, where this last value was known with confidence. Data before transformation from 294 of the 337 sites are plotted in Fig. 1, with a calculated linear regression line superimposed for each of the three grassland development classes and for conifer forest plantations. Regressions of the log-transformed Olsen-phosphorus data against precipitation for a single amalgamated grassland class and for conifer forest, showing confidence intervals, are summarised in Fig. 2. The enhancement of Olsen-phosphorus levels from afforestation was of similar magnitude over the precipitation range of the survey with similar decline in Olsen-phosphorus with increasing precipitation, under both forest and grassland.

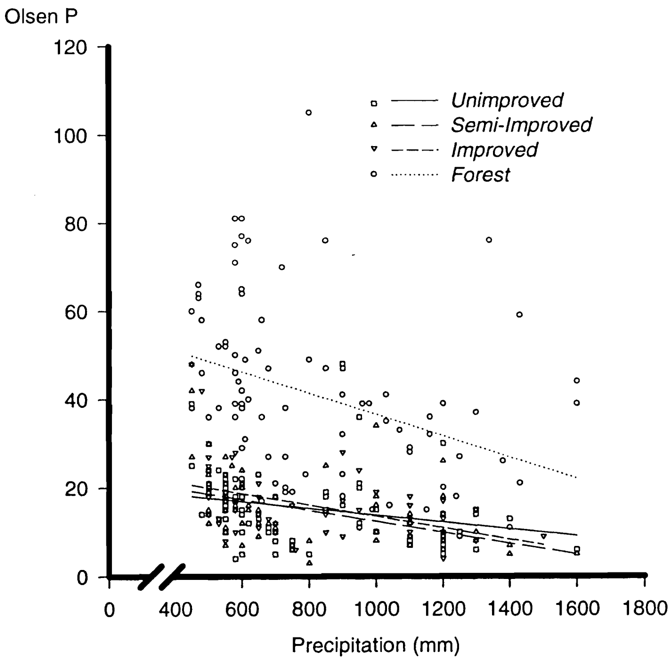

FIG. 1–Relationship between Olsen-phosphorus (ppm) and precipitation (mm) for soils from unimproved grassland, semi-improved grassland, improved pasture, and conifer forest.

We could detect no relationship between forest plantation age and either Olsen-phosphorus or inorganic phosphorus, nor could we discern any apparent effect of conifer species. We would conclude from this survey, therefore, that for plantations of 20 years of 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 the earliest observation 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

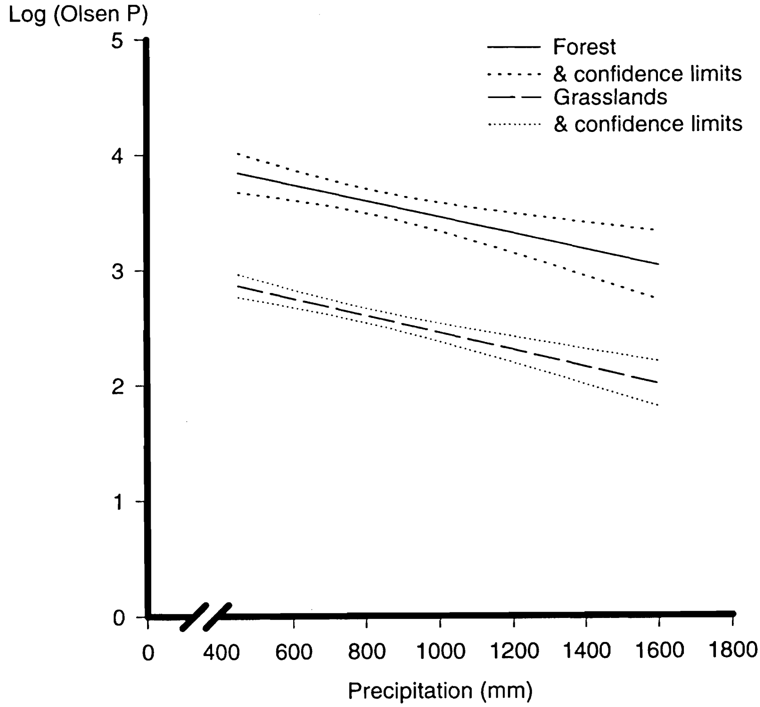

FIG. 2–Relationship between logarithmic transformed Olsen-phosphorus (ppm) and precipitation (mm) for soils from aggregated grasslands and pasture, and forest, with 95% confidence limits on each relationship.
Y (grassland) = 3.197 – 0.000746x
Y (forest) = 4.158 – 0.000703x

horticulture after 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 after conifers in the Canterbury high country has been provided by Belton (1992), Davis & Lang (1991), and Ledgard & Baker (1982). Davis & Lang (1991) also identified many substantial differences in soil chemical properties when they compared existing plantations with adjacent grasslands. They used more intensive soil analyses on a limited number of sites, and recorded marked variation among sites. 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 to compare with records from grassland topsoils. Issues warranting discussion here include the distribution, magnitude, and possible processes involved in apparent conifer effects on topsoil phosphorus.

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 nitrogen, and inorganic phosphorus indicated that soil groups with naturally higher levels of inorganic phosphorus (brown-grey earths, yellow-grey earths, and youthful yellow-brown earths on loess) had the largest pH depressions and greatest nitrogen increases attributable to conifer plantations. We presumed that these nitrogen 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 16–40%) in inorganic phosphorus associated with conifer plantations, compared with the other soil groups in Table 1 (group means 70–140% increase in inorganic phosphorus). 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 was 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 nitrogen 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 phosphorus and even slight increases in total phosphorus, were their sites 6 and 7, ascribed to the Mackenzie soil set within the dry-hygrous HCYBE group. The same soil group is also identified in Table 1 of this paper as that with the largest proportional increase from grassland to conifer plantation in inorganic phosphorus. In the Davis & Lang study, the five central Canterbury sites, which all belong to the hygrous HCYBE group, showed smaller increases in inorganic phosphorus from grassland to conifer plantation, as did soils of the same group in this paper. The increase in inorganic phosphorus in the hygrous HCYBE soils in the Davis & Lang study was accompanied by a small general decrease in total topsoil phosphorus from grassland to plantation. From their graphs of total and inorganic phosphorus we interpret that almost all sites exhibited a decrease from grassland to conifer plantation in organic phosphorus.

Davis & Lang (1991), following the conclusions of Fisher & Stone (1969), inferred substantial net mineralisation of residual grassland organic matter during occupancy by conifers. Data in our Table 1 cannot be used to prove this hypothesis because we have no organic phosphorus data from forest samples, but the increase in inorganic phosphorus in all soil groups between grassland and forest is consistent with the Davis & Lang thesis.

Within the range of stand ages of the Ledgard & Belton (1985) soil samples that we were able to examine, we were unable to identify any influence of stand age or development on inorganic phosphorus levels. 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-phosphorus values. 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" as in HF-extractable organic nitrogen, available nitrogen, and extractable phosphorus 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. We note that Davis & Lang (1991) in their comparison of grassland and younger conifer stands in central Canterbury recorded generally much greater mineralisable nitrogen and sulphate-sulphur from soils under conifers. At their older stands in the Mackenzie country the influence of forest was principally shown by increases in Bray-2 phosphorus and Olsen-phosphorus.

Sources of Variability and Pattern in Olsen-phosphorus in Grassland and Plantation

The variability in Olsen-phosphorus results, along with the underlying order that can be discerned in them warrants comment. Whereas coefficients of variation in inorganic phosphorus were, for most soil groups, much less for conifer plantation collections than for unimproved grassland records (Table 1), Olsen-phosphorus values showed high coefficients of variation under conifers and under unimproved grasslands, for several soil groups (Table 2). We interpreted from the correlation of Olsen-phosphorus values with inorganic phosphorus values in the conifer plantation samples (r=0.685**) that almost half of the variation in Olsen-phosphorus was associated with variation in inorganic phosphorus, itself pedogenetically influenced by precipitation, topsoils of the drier soil groups tending to have higher levels of inorganic phosphorus. Harrison (1989, p.48) in his review of phosphorus distribution and cycling in European forests, recognised bicarbonate-extracted Olsen-phosphorus as "labile inorganic and organic phosphorus". Confirmation of this phenomenon in New Zealand high country soils has been provided by Condron *et al.* (1996) who demonstrated the reduction in the organic component or the enhancement of the inorganic component of bicarbonate-extracted phosphorus from soil samples taken from three of the eight field trial sites of Davis & Lang (1991).

We believe that a substantial proportion of the variation in Olsen-phosphorus 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 (O'Connor 1983). We suspect that uneven distribution of animal returns may contribute to high variability in grassland Olsen-phosphorus values (Allan 1985; Thorrold *et al.* 1985; O'Connor & Harris 1992). We believe that this also accounts for the failure of our survey to demonstrate significant differences between grassland development classes.

In their paired site comparisons, Davis & Lang (1991) recorded that proportional increases in Olsen-phosphorus 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). In topsoils from their central Canterbury sites, mostly under immature stands, Olsen-phosphorus levels seldom exceeded 10 ppm, scarcely reaching 1% of total phosphorus. Their Mackenzie Basin conifer samples under stands 31 years or older showed Olsen-phosphorus values ranging from 40 to 70 ppm, 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 in Olsen-phosphorus from grassland to conifer plantation was from two-fold to four-fold. For soil groups, the mean increase in Olsen-phosphorus 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-phosphorus under conifers was similar for all soil groups. Likewise, the closely similar slope of regression lines in Fig. 2 showed the similarity of influence of increasing precipitation on transformed Olsen-phosphorus values, regardless of vegetation.

Our suggestion is that the phenomenon of Olsen-phosphorus 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 well-developed conifer stands although Hawke & O'Connor (1993) recorded that Olsen-phosphorus enhancement may have occurred in stands as young as 13 years at Tikitere, near Rotorua.

Significance of Olsen-phosphorus Enhancement

Sparling *et al.* (1985) demonstrated the substantial enhancement of Olsen-phosphorus 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 phosphorus after fumigation of moist soil, led them to suggest that the enhanced Olsen-phosphorus in the dried soils could be accounted for almost entirely by the release of phosphorus 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 phosphorus was likely to be important as soils with organic carbon content of >2%, predominantly under permanent pasture, having $NaHCO_3$-extractable phosphorus 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 phosphorus in elevating Olsen-phosphorus values in air-dried samples of hygrous HCYBEs in particular. 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 interpret the difference in soil Olsen-phosphorus levels between grasslands and mature forest stands to reflect a real difference in soil microbial systems (Condron *et al.* 1996; Condron 1996), even though this difference may be expressed more clearly as an outcome of soil drying.

We emphasise that the important phenomenon in our Olsen-phosphorus data is the substantial margin by which the conifer plantation values exceed the grassland values for comparable soils (Table 3, Fig. 2). This is also true for inorganic phosphorus (P_i) values (Table 1). From the regression demonstrated in Fig. 2 and both the background soil data from studies referred to in Appendix 1 and the data of Davis & Lang (1991), we interpret a general outline of the phosphorus regimes that occur across the range of our survey. In the driest soils (c. 500 mm precipitation) we estimate Olsen-phosphorus values under conifers to be around 7% of total topsoil phosphorus, that is about 50 mg/kg of 700 mg/kg, with approximately one-third of total phosphorus as organic. At the wetter end of our sampling range (c. 1600 mm precipitation), our estimate of Olsen-phosphorus falls to around 2 or 3% of total topsoil phosphorus, that is about 20 mg/kg of 900 mg/kg, with approximately two-thirds of total phosphorus as organic. Again we emphasise that for our wetter samples, our estimate of the mean Olsen-phosphorus values was several times greater than those from the much younger plantations in central Canterbury, studied by Davis & Lang (1991). Whether the general feature of enhanced Olsen-phosphorus which we associate with mature plantations has involved "nutrient pumping" as was earlier suggested (O'Connor 1986), we cannot fairly conclude from our data. Davis & Lang (1991) indicated its relevance to the dry hygrous Mackenzie sites. The substantial increase in inorganic phosphorus recorded for hygrous soils in Table 1, may be outweighed by a decrease in organic phosphorus, as it was for the younger stands of Davis & Lang in central Canterbury. This issue must await an extension of the thorough analyses of Davis & Lang (1991) and Condron *et al.* (1996) to a wider range of paired sites.

Nutrient balances are 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). The benefits of increased mineralisation of organic matter by conifers in New Zealand montane grassland soils to both trees and other plants have been demonstrated unequivocally by Davis & Lang (1991) and Davis (1995). The integrated dynamics of phosphorus cycling with the cycling of carbon, nitrogen, and sulphur 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 1995), 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.

CONCLUSION

Regardless of the further scientific explanations which must be awaited, the practical significance of the present findings cannot easily be avoided. The phenomenon of Olsen-phosphorus and P_i enhancement belongs to the whole geographic range of the montane zone of the Canterbury high country. Because a substantial proportion of the greatly enhanced available phosphorus seems to be associated with increased mineralisation, we interpret the Olsen-phosphorus 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. 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 terrain.

REFERENCES

ALLAN, B.E. 1985: Grazing effects on pasture and animal production from oversown tussock grassland. *Proceedings of the New Zealand Grassland Association 46*: 119–25.

BALLARD, R. 1970: The phosphate status of the soils of Riverhead Forest in relation to growth of radiata pine. *New Zealand Journal of Forestry 15*: 88–99.

BELTON, M.C. 1991: Forestry: A sustainable landuse for degraded high country lands. *New Zealand Forestry: 36(1)*: 19–22.

———1992: Prospects for forestry as a beneficial land use on degraded high country grasslands. Pp.371–5 *in* Henriques, P. (Ed.) "Sustainable Land Management", Proceedings of the International Conference on Sustainable Land Management, Napier, November 1991.

BELTON, M.C.; LEDGARD, N.J. 1984: A new map of the rainfall pattern below 1600 mm for the Canterbury high country. *Weather and Climate 4*: 63–5.

BELTON, M.C.; O'CONNOR, K.F.; ROBSON, A.B. 1990: Phosphorus levels in high country topsoils under exotic conifers and grasslands. New Zealand Soil Society Conference, Alexandra, New Zealand, November.

BINKLEY, D. 1995: The influence of tree species on forest soils—Processes and patterns. Pp.1–33 *in* Mead, D.J.; Cornforth, I.S. (Ed.) Proceedings of the Trees and Soils Workshop, Lincoln University, 28 February-2 March 1994. *Agronomy Society of New Zealand, Special Publication No. 10.*

BIRCH, H.F. 1958: The effect of soil drying on humus decomposition and nitrogen availability. *Plant and Soil 10*: 9–31.

BLAKEMORE, L.C.; SEARLE, P.C.; DALY, B.K. 1972: Soil Bureau laboratory methods. *New Zealand Soil Bureau Scientific Report 10A.*

COCKAYNE, A.H. 1914: *Pinus radiata* plantations: effect on soil fertility. *New Zealand Journal of Agriculture 8*: 409–10.

COLE, C.V.; SANDFORD, R.L. Jr. 1989: Biological aspects of the phosphorus cycle. Pp.10–16 *in* Tiessen, H. (Ed.) "Phosphorus Cycles in Terrestrial and Aquatic Systems Regional Workshop 1: Europe". Saskatoon, Saskatchewan Institute of Pedology.

CONDRON, L.M. 1996: Trees and soil fertility: a New Zealand perspective. Proceedings of Australian and New Zealand Soils Conference, Vol.2 Oral Papers: 47–8.

CONDRON, L.M.; DAVIS, M.R.; NEWMAN, R.H.; CORNFORTH, I.S. 1996: Influence of conifers on the forms of phosphorus in selected New Zealand soils. *Biology and Fertility of Soils 21*: 37–42.

CORNFORTH, I.S.; SINCLAIR, A.G. (Comp.) 1984: "Fertiliser and Lime Recommendations for Pastures and Crops in New Zealand". Ministry of Agriculture and Fisheries, Wellington.

DAVIS, M.R. 1995: Influence of radiata pine seedlings on chemical properties of some New Zealand montane grassland soils. *Plant and Soil 176*: 255–62.

DAVIS, M.R.; LANG, M.H. 1991: Increased nutrient availability in topsoils under conifers in the South Island high country. *New Zealand Journal of Forestry Science 21(2/3)*: 165–79.

FISHER, R.F. 1990: Amelioration of soils by trees. Pp.290–300 *in* Gessel, S.P.; Lacarte, D.S.; Weetman, G.F.; Powers, R.F. (Ed.) "Sustained Productivity of Forest Soils". University of British Columbia Press, Vancouver.

FISHER, R.F.; STONE, E.L. 1969: Increased availability of nitrogen and phosphorus in the root zone of conifers. *Soil Science Society of America Proceedings 33(6)*: 955–61.

GRIGG, J.L. 1965: Inorganic phosphorus fractions in South Island soils and their solubility in commonly used extracting solutions. *New Zealand Journal of Agricultural Research 8*: 313–26.

HARRISON, A.F. 1989: Phosphorus distribution and cycling in European fresh ecosystems. Pp.42–76 *in* Tiessen, H. (Ed.) "Phosphorus Cycles in Terrestrial and Aquatic Systems Regional Workshop, 1: Europe". Saskatoon, Saskatchewan Institute of Pedology.

HAWKE, M.F.; O'CONNOR, M.B. 1993: Soil pH and nutrient levels at Tikitere Agroforestry research area. *New Zealand Journal of Forestry Science 23(1)*: 40–8.

HORNUNG, M. 1985: Acidification of soils by trees and forests. *Soil Use and Management 1*: 24–8.

LEDGARD, N.J. 1993: Forestry in New Zealand southern high country. Proceedings of NATO Advanced Research Workshop, 18–23 June 1991, Laugarbaten, Iceland.

LEDGARD, N.J.; BAKER, G.C. 1982: Growing trees in the high country. III. Uses. *Tussock Grasslands and Mountain Lands Institute Review 41*: 29–37.

LEDGARD, N.J.; BELTON, M.C. 1985: Exotic trees in the Canterbury high country. *New Zealand Journal of Forestry Science 15*: 298–323.

MARTIN, G.; GARDEN, P.; MEISTER, A.; PENNO, B.; SHEATH, G.; STEPHENSON, G.; URQUHART, R. 1994: South Island High Country Review: Final Report from the Working Party on Sustainable Land Management, New Zealand Government, Wellington.

McFADDEN, G.H. 1969: A study of some soils of agricultural importance in the Ashburton Gorge region. M.Agr.Sc.Thesis, Lincoln College, University of New Zealand.

McINTOSH, P.D.; BACKHOLM, G.; SMITH, J. 1981: Soil variation related to landscape and vegetation in North Otago hill country. *New Zealand Journal of Science 24*: 224–44.

MILLER, R.B. 1968: Soil chemistry. *In* New Zealand Soil Bureau "General Survey of Soils of South Island, New Zealand". *New Zealand Department of Science and Industrial Research, Soil Bureau Bulletin 27.*

MOLLOY, B.P.J. 1969: Recent history of the vegetation. Pp.340–60 *in* Knox, G.A. (Ed.) "Natural History of Canterbury". Reed, Wellington.

NEW ZEALAND SOIL BUREAU 1968a: "General Survey of Soils of South Island, New Zealand". *New Zealand Department of Scientific and Industrial Research, Soil Bureau Bulletin 27.*

———1968b: "Soils of New Zealand Part 3". *New Zealand Department of Scientific and Industrial Research, Soil Bureau Bulletin 26(3).*

NORDMEYER, A.H.; KELLAND, C.M.; EVANS, G.R.; LEDGARD, N.J. 1987: Nutrients and the restoration of mountain forests in New Zealand. Pp.145–54 *in* Fujimori, T.; Kimurai, M. (Ed.) "Human Impacts and the Management of Mountain Forests". Forest Research Institute, Ibarahi, Japan.

O'CONNOR, K.F. 1983: Nitrogen balances in natural grasslands and extensively managed grassland systems. *New Zealand Journal of Ecology 6*: 1–18.

———1986: Roles for forestry in high country land use. *Tussock Grasslands and Mountain Lands Institute Review 43*: 83–94.

O'CONNOR, K.F.; HARRIS, P.S. 1992: Biophysical and cultural factors affecting the sustainability of high country pastoral land uses. Pp.304–13 *in* Henriques, P. (Ed.) "Sustainable Land Management". Proceedings of the International Conference on Sustainable Land Management, Napier, November 1991.

PARTON, W.J.; STEWART, J.W.B.; COLE, C.V. 1988: Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry 5*: 109–31.

ROSOMAN, G. 1994: "The Plantation Effect". Greenpeace New Zealand, Auckland. 48 p.

SAS 1990: "SAS/STATISTICS: Reference, Version 6", first edition. SAS Institute Inc., Cary, North Carolina

SPARLING, G.R.; WHALE, K.N.; RAMSAY, A.J. 1985: Quantifying the contribution from the soil microbial biomass to extractable P levels of fresh air-dried soils. *Australian Journal of Soil Research 23*: 613–21.

STEVENSON, F.J. 1986: The phosphorus cycle. Pp.231–84 *in* Stevenson, F.J. "Cycles of Soil C, N, P and S Micronutrients". John Wiley and Sons, New York.

TATE, K.R. 1984: The biological transformations of P in soil. *Plant and Soil 76*: 245–56.

TAYLOR, N.H.; POHLEN, I.J. 1962: Soil survey method. *New Zealand Department of Scientific and Industrial Research, Soil Bureau Bulletin 25.*

THAPA, B.K. 1956: Studies on the accumulation and composition of organic matter in grassland soils with particular reference to organic phosphorus, carbon, nitrogen and sulphur. M.Agr.Sc.Thesis, Lincoln College, University of New Zealand.

THORROLD, B.S.; O'CONNOR, K.F.; WHITE, J.G.H. 1985: Management influences on sheep behaviour, dung distribution and soil phosphate. *Proceedings of the New Zealand Grassland Association 46*: 127–34.

VELLEMAN, P.F.; HOAGLIN, D.C. 1981: "Applications, Basics and Computing of Exploratory Data Analysis". Duxbury Press, Wadsworth Inc., Belmont, California.

WALKER, T.W.; ADAMS, A.F.R. 1958: Studies on soil organic matter: I. *Soil Science 85*: 307–18.

———1959: Studies on soil organic matter: II. *Soil Science 87*: 1–10.

WEBB, T.H. 1976: Pedological studies of soils of the Tekapo set in east Lake Pukaki region, South Canterbury, New Zealand. M.Agr.Sc.Thesis, Lincoln College, University of Canterbury.

WELLS, N.; SAUNDERS, W.M.H. 1960: Soil studies using sweet vernal to assess element availability. IV. Phosphorus. *New Zealand Journal of Agricultural Research 3*: 279–99.

WILL, G.M. 1993: Sustainable plantation forestry in New Zealand. Pp.19–21 *in* Ryde, D.; Bezar, H. (Ed.) "1992 Agricultural Frontiers: Opportunities and Risks". Proceedings of the New Zealand Institute of Agricultural Science and the New Zealand Society for Horticultural Science Annual Convention.

WILL, G.M.; BALLARD, R. 1976: Radiata pine - soil degrader or improver, *New Zealand Journal of Forestry 21*: 248–52.

WILLIAMS, P.A.; NES, P.; O'CONNOR, K.F. 1977: Macro-element pools and fluxes in tall tussock (*Chionochloa*) grasslands, Canterbury, New Zealand. *New Zealand Journal of Botany 15*: 443–76.

WILLIAMS, P.A.; MUGAMBI, S.; NES, P.; O'CONNOR, K.F. 1978: Macro-element composition of tall-tussocks (*Chionochloa*) in the South Island, New Zealand and their relationship with soil chemical properties. *New Zealand Journal of Botany 16*: 479–98.

APPENDIX 1

SOURCES OF DATA FOR NITROGEN, PHOSPHORUS, AND PH FOR TOPSOIL 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, nitrogen, and inorganic phosphorus, 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. Where there is a predominant source for any soil group the reference is in bold type.

Soil group	Sources
Brown-grey earths	Thapa (1956); Walker & Adams (1959); Wells & Saunders (1960); R.L.Parfitt & L.C.Blakemore (pers. comm.)
Yellow-grey earths	**McIntosh *et al.* (1981)**; Thapa (1956); Walker & Adams (1959); R.L.Parfitt & L.C.Blakemore (pers. comm.)
Dry hygrous yellow-brown earths	McFadden (1969); New Zealand Soil Bureau (1968b); Thapa (1956); Walker & Adams (1958, 1959); **Webb (1976)**; R.L.Parfitt & L.C.Blakemore (pers. comm.)
Hygrous yellow-brown earths	Thapa (1956); Walker & Adams (1958, 1959); **P.J.Tonkin & K.F.O'Connor (pers. comm.)**
Youthful soils from loess	McFadden (1969); Thapa (1956); Walker & Adams (1958)
Recent soils from alluvium	McFadden (1969; P.J.Tonkin & K.F.O'Connor (pers. comm.)

Some clarification is needed of the relationship of phosphorus (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 phosphorus) and P_o (organic phosphorus) 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 phosphorus 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 phosphorus even though these may sometimes represent a slight over-estimate 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 vary 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 has been 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 personal communications 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.